Quelles propriétés racinaires et quelles espèces-outils pour la stabilisation des points chauds de dégradation en Chine du Sud ?

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Quelles propriétés racinaires et quelles espèces-outils pour la stabilisation des points chauds de dégradation en Chine du Sud ?

Which root properties and which tool-species can best stabilize degradation hotspots in Southern China?

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Je ne sais pas de plus noble mission que celle d'aider la nature
à reconstituer dans nos montagnes l'ordre qu'elle avait si bien établi et
que seule l'imprévoyance de l'homme a changé en un inévitable chaos.

Prosper Demontzey (1831-1898), ingénieur des Eaux et Forêts,
Instigateur de la restauration des terrains de montagne

Il sauvegardait toute parcelle d'humanité.
Le périmètre de la Dourbie supérieure est à cet égard un modèle.
Il avait la joie de constater que la population ne diminuait pas dans les villages
entourant immédiatement le massif de l'Aigoual.

Charles Flahaut (1852-1935), botaniste,
évoquant George Fabre (1844-1911), garde général des Eaux et Forêts,
avec qui il a mené la reforestation du massif de l'Aigoual menacé de déprise agricole

Apprends auprès de celui qui est ignorant comme avec le savant.

Ptah Hotep, préfet de l'Egypte antique, vers 2400 av. J.-C.

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RÉSUMÉ

La Chine est actuellement confrontée à de sérieux problèmes environnementaux et est listée parmi les pays qui contribuent le plus à la pollution et à la destruction de l'environnement mondial. En particulier, la Chine du Sud est une zone naturellement sujette aux glissements de terrain à cause de conditions tectoniques, climatiques et anthropiques particulièrement défavorables. Depuis la fin des années 1990, l'Etat chinois a mis en place des politiques de reforestation de grande envergure. Mais il existe des lacunes de connaissances qu'il convient de combler. En particulier, le choix des espèces les plus adaptées n'est pas aisé parce que les processus par lesquels les plantes stabilisent les pentes ont besoin d'être mieux compris.

En introduction, afin de préciser les périmètres qui cadrent cette thèse, sont présentées la situation de la Chine du Sud au regard des glissements de terrain, la discipline d'éco-ingénierie et les solutions qu'elle peut apporter. Ainsi, ce travail (i) se concentre sur des espèces végétales locales, (ii) se limite aux glissements de terrain superficiels, et (iii) concerne à la fois les processus mécaniques et hydriques entre le sol et les racines. A l'intérieur de ces cadres, la thèse a pour objectif de répondre à la question scientifique : quels sont les propriétés racinaires qui influencent la stabilisation des pentes ? La réflexion est ensuite appliquée aux plantes de Chine du Sud afin d'identifier les meilleures espèces-outils. Pour répondre à cette question, à la fois les données de terrain (en Chine du Sud), les expériences de laboratoire (en France) et la formulation de concepts sont mobilisées. Les résultats sont organisés en deux chapitres. Le premier chapitre pose la question de l'efficacité de la présence de racines pour stabiliser les pentes, tout d'abord sous l'angle des processus mécaniques, puis sous l'angle des processus hydriques. Le deuxième chapitre permet d'identifier un panel de traits pertinents et non redondants évaluant l'efficacité d'une espèce pour la stabilisation des pentes puis s'appuie sur ce panel afin de sélectionner les espèces chinoises les plus efficaces. Enfin, la discussion aborde les limites de ce travail et propose de nouvelles pistes de recherche.

Du point de vue mécanique comme du point de vue hydrique, c'est la conjonction des effets des racines de structure et des racines fines qui importe. Les racines de structure sans racines fines ne sont pas optimales et peuvent même faire apparaître des lignes de fragilité. Plus précisément, les racines de structure sont particulièrement bienvenues vers l'aval de la pente pour des raisons à la fois mécaniques et hydriques. Les racines fines seules ne sont pas optimales non plus, elles peuvent faire apparaître localement des zones de faiblesse qui, si elles sont proches, participeront au déclenchement d'un glissement de terrain. Des ramifications racinaires denses améliorent la stabilité mécanique. Orientées vers l'aval de la pente, elles améliorent la stabilité hydrique. Les autres traits racinaires pertinents pour évaluer l'efficacité des racines à stabiliser le sol sont la contrainte et la déformation maximale en tension, la concentration en azote et la concentration en sucres solubles. Les espèces les plus efficaces parmi les neuf espèces pionnières mesurées sur les pentes chinoises sont *Pueraria stricta,* une légumineuse originaire d'Asie du Sud-Est et plantée dans le cadre des programmes de reforestation, et *Artemisia codonocephala*, une Asteracée native de Chine du Sud. Des préconisations concernant les neuf espèces sont présentées, pour l'utilisation de leurs qualités en éco-ingénierie.

Les limites de cette thèse pointent la difficulté du choix des indicateurs et de leur évolution dans le temps. Une autre limite réside en la difficulté à évaluer les relations entre les racines et le sol, car la seule résistance des racines n'est pas suffisante pour empêcher le sol de glisser. Enfin, l'intégration spatiale des propriétés racinaires demeure malaisée. En conclusion, cette thèse contribue à améliorer les connaissances concernant le matériau végétal à disposition sur les montagnes de Chine du Sud. Ses résultats viendront optimiser les actions d'éco-ingénierie en stabilité des pentes. Elle améliore également la connaissance des processus en jeu entre les racines et leur milieu lors d'un glissement de terrain.

Mots-clefs : glissements de terrain, éco-ingénierie, Grain for Green, traits racinaires, résistance au cisaillement

ABSTRACT

China is currently facing serious environmental issues and is listed among the countries that contribute most to pollution and destruction of the global environment. Particularly, Southern China is naturally prone to landslides because of unfavourable tectonic, climatic and anthropogenic conditions. Since the late 1990s, the Chinese government has implemented policies of large-scale reforestation, but lacks of knowledge still exist. In particular, the question of the most suitable species is still pending because processes by which roots stabilize slopes need to be better understood.

In order to clarify the boundaries within which this work is situated, the introduction presents the context in Southern China with regard to landslides, eco-engineering discipline, and the solutions it brings. Thus, this study (i) focuses on the use of local plant species, (ii) concentrates on the study of superficial landslides, and (iii) addresses mechanical as well as hydrological processes between roots and soil. Within these frameworks, this thesis aims to answer the following scientific question: which root properties influence slope stability? The reflexion is then applied to Southern China, in order to identify the best tool-species for eco-engineering. To answer this question, field data (in Southern China), laboratory experiments (in France) and the formulation of concepts are mobilized. The results are organized into two chapters. The first chapter raises the question of the effectiveness of the presence of roots to stabilize slopes, first in terms of mechanical processes, then in terms of hydraulic processes. The second chapter identifies a panel of relevant and non-redundant traits assessing a given species effectiveness in slope stabilization, and then draws on that panel to select the most efficient Chinese species. Finally, the discussion addresses the limitations of that work and suggests new avenues of research.

From the mechanical as well as the hydraulic viewpoint, the conjunction of structural roots and fine roots is determinant. Structural roots alone are not optimal and may even bring up lines of weakness. Specifically, for both mechanical and hydric reasons, structural roots are particularly efficient when they grow downslope. Fine roots alone are not optimal either, as they can produce local areas of weakness which, if they are close, can participate in the triggering of a landslide. The branching organization is also particularly important: dense throughout the root profile, branches improve the mechanical stability. Oriented downslope, branching forks improve underground water flow and thus hydraulic stability.

Other root traits relevant to assessing the root effectiveness to soil stabilization are maximum tensile stress and strain, nitrogen concentration as well as concentration in water-soluble sugars. The most efficient species among nine pioneer species measured on the Chinese slopes are *Pueraria stricta*, a legume native from Southeast Asia which plantation happened from reforestation programs, and *Artemisia codonocephala*, a spontaneous Asteraceae native from Southern China. Recommendations regarding the nine species are presented for the use of their characteristics in eco-engineering.

The limits of this thesis point out the difficulty to choose indicators and to follow their evolution over time. Another limitation lies in the difficulty to assess the relationship between roots and soil, as the only root resistance is not sufficient to prevent soil from sliding. Finally, the spatial integration of root properties remains challenging.

In conclusion, this thesis contributes to improve the knowledge of the plant material available in the mountains of Southern China. Its results will optimize eco-engineering actions related to slope stability. It also upgrades the knowledge about processes at stake between roots and their environment during a landslide.

Keywords: landslides, eco-engineering, Grain for Green programme, root traits, shear strength

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► Ghestem. Relationships between root traits of plants growing on unstable slopes. En préparation.

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INTRODUCTION GÉNÉRALE

I. PRÉSENTATION DU CONTEXTE ET PÉRIMÈTRE DE LA THÈSE

I. 1. Contexte géographique, politique et sociologique de la thèse

I. 1. a. Les dégâts des glissements de terrain dans le Monde

Parmi les fléaux naturels, les glissements de terrain sont reconnus comme étant la 7ème cause de mortalité après les tempêtes, les inondations, les sécheresses, les tremblements de terre, les explosions volcaniques et les températures extrêmes, causant en moyenne 800 à 1 000 morts chaque année sur les 20 dernières années (statistiques du Centre de recherche sur l'épidémiologie des fléaux naturels, CRED, www.cred.be). A cause de la qualité variable des compte-rendus et de la documentation sur les glissements de terrain selon les pays, il est difficile de quantifier rigoureusement leur distribution et leurs dégâts dans le monde (Sidle & Ochiai 2006) De plus, l'impact socio-économique des glissements de terrain est sous-estimé parce qu'ils sont souvent associés à d'autres fléaux naturels (Kalsnes et al. 2008). Afin de dresser une vue globale de la distribution des glissements de terrain et de leurs dégâts, on peut avancer que l'Asie a subi 220 glissements de terrain durant le XXème siècle ; c'est de loin la région qui compte le plus de glissements. Mais les glissements de terrain survenus en Amérique du Nord, du Sud et centrale ont causé davantage de morts et de blessés (plus de 25 000 personnes durant la même période). Les glissements de terrain en Europe ont eu pour conséquence les plus grandes pertes matérielles : environ 23 millions US$ par glissement de terrain en moyenne (Dai et al. 2002, Schuster & Fleming 1986).

I. 1. b. Situation en Chine du Sud

La Chine du Sud-Est est une zone naturellement sujette aux glissements de terrain parce qu'elle cumule une combinaison de conditions dangereuses. Les conditions tectoniques de l'Himalaya (Upreti et al. 2008) s'ajoutent aux conditions climatiques des régions sub-tropicales alternant une période de mousson après une période très sèche (Larsen & Simon 1993) et aux conditions anthropiques de pays en phase de développement rapide.
Tout comme les incendies, les glissements de terrain font partie des perturbations qui, en Chine comme ailleurs, impactent naturellement les écosystèmes (Veblen et al. 1992). Deux tiers de la Chine sont constitués de collines et de montagnes à pentes abruptes (Stokes et al. 2010). En Chine du Sud en particulier, la forte activité sismique induit de nombreux glissements de terrain comme dégâts secondaires des tremblements de terre (Wang et al. 2008, Yin et al. 2008).
Les causes anthropiques des glissements de terrain, quant à elles, sont de plus en plus importantes en Chine. L'érosion et les glissements de terrain sont le résultat de la déforestation (Démurger et al. 2005), de mauvaises pratiques agricoles (Liu & Diamond 2005) et de la sur-exploitation des ressources dans les 50 dernières années (Stokes et al. 2008, *encadré i*). La Chine possède une surface totale d'espaces boisés de 175 millions d'hectares et un volume sur pied de 12.5 milliards m^3, la plaçant respectivement au cinquième et septième rangs mondiaux. Pourtant sa superficie boisée ne représente que 4% de la superficie mondiale et sa réserve de bois sur pied moins de 3 % des réserves mondiales (Démurger et al. 2005). Les Chinois disposent en moyenne de 0,1 ha de forêt/personne, alors que la moyenne mondiale est de 0,6 ha/personne (Liu & Diamond 2005). Enfin, son stock de bois sur pied représente moins de 10 m^3 par habitant pour une moyenne mondiale d'environ 66 m^3 (Sixième inventaire forestier de la Chine, mené entre 1999 et 2003, dans : China Daily, 19 janvier 2005, NB : Les chiffres concernant un grand pays comme la Chine sont toujours à considérer avec précaution). Un nouveau problème

crucial en Chine est la construction de pistes reliant les villages aux bourgs et aux villes. A cause du rapide développement économique et urbain, les glissements de terrain associés aux activités humaines et au développement des infrastructures comptent pour 80% des glissements de terrain au niveau national (Yin 2008). Un inventaire le long de la vallée de la Salween dans le Yunnan (où se situe notre site d'étude) a montré que les pertes de sol à cause de la construction de pistes représentent au moins 80% des pertes totales de sol, 600 fois plus que les volumes les plus importants observés aux Etats-Unis (Sidle 2007). La Chine doit développer et désenclaver les zones rurales en montagne tout en limitant les risques de glissements de terrain.

Encadré i : Historique de la déforestation en Chine

La Chine a longtemps été un pays principalement rural, bien que cette tendance soit en train d'évoluer : la population urbaine représentait 29,4% de la population totale en 1995, 40,5% en 2003 et 45,7% en 2009 (Bureau national des statistiques chinoises - mis en ligne le 16 février 2009 par le ministère de l'agriculture chinois, Villalonga 2009b).

Cette lente mutation s'explique par une histoire particulière. La Chine a connu une longue période d'instabilité politique de 1912, date de la chute du Dernier Empereur et instauration de la République de Chine, à 1949, date de la proclamation de la République Populaire par Mao Zedong. Ensuite, pendant une dizaine d'années, Mao Zedong s'efforcera encore de repousser les frontières de son pays, d'assurer le calme intérieur et la reconnaissance de la Chine à l'extérieur. C'est seulement à partir des années 60 que ce pays immense se lance dans sa révolution industrielle, initiée par le Grand Bond en Avant (1958-1960).

La Chine s'est alors peu à peu métamorphosée en « l'usine du monde » que l'on connaît actuellement. Cette métamorphose a été possible par une exploitation sans précédent des ressources naturelles, en particulier des forêts. Il s'agissait de déboiser afin de gagner des terres agricoles, et d'alimenter en carburant les fourneaux des industries lourdes. Dès le début des années 1960, 136 Bureaux des Forêts ont été progressivement mis en place dans les zones où les récoltes de bois étaient les plus importantes, afin d'améliorer la production des forêts (Xu et al. 2006). Dans leurs premières années, ces bureaux devaient fonctionner avec des moyens limités en termes d'équipements, d'infrastructures, de capital. Comme toutes les entreprises d'Etat de l'époque, ils devaient subvenir à leurs propres besoins de fonctionnement comme les salaires, les frais de santé, l'éducation et l'embauche des enfants de leurs employés, donc de plus en plus nombreux (Yin 1998). Comme la vente de bois était la principale source de revenus de ces Bureaux, la surexploitation forestière est devenue inévitable. Puisque leur autonomie et leur légitimité était mise à mal, la déforestation clandestine faisait rage, les taux de régénération des forêts étaient très faibles, alors que la structure des peuplements était déstabilisée vers les jeunes stades.

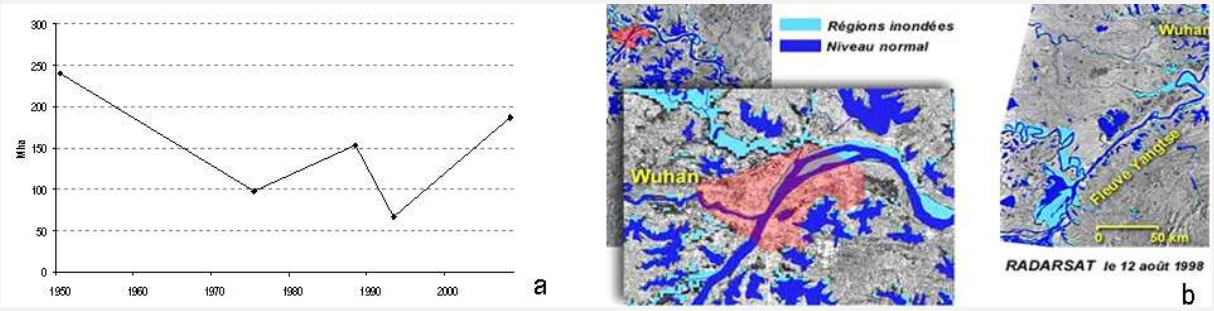
Malheureusement, la situation environnementale des zones agricoles ne valait guère mieux. Les terres agricoles, comme tout moyen de production, ont été collectivisées en masse et subitement (1958). Le manque de préparation de cette opération de collectivisation et le manque de connaissances techniques des nouveaux responsables conduit à une chute dramatique des rendements agricoles. A cela s'est ajoutée la Révolution Culturelle (1966-1970), qui a eu un impact tragique sur la population rurale, saignée pour alimenter les villes, et sur les ressources naturelles, à tel point « qu'il n'y avait plus une feuille sur les arbres, ni un oiseau sur les branches » (communication personnelle d'un Chinois), puisque toute nourriture était avidement recherchée.

A la mort de Mao Zedong (1976), Deng Xiaoping, conscient de l'impasse dans laquelle s'enfonçait le pays tout entier, propose une ouverture vers l'économie de marché en privatisant certains moyens de production. En 1981, certaines terres agricoles et certaines forêts sont restituées à des collectifs villageois, qui gèrent ensuite les droits d'usage entre leurs membres. Depuis cette période, environ ½ des forêts est gérée par l'Etat et ½ par des collectifs (Miao et al. 2004). Cette rétrocession des droits d'usage de l'Etat central vers les collectifs villageois s'est traduite de différentes façons selon les contextes locaux. Schématiquement, trois types de systèmes se sont installés, qui perdurent à l'heure actuelle. (a) Soit les droits d'usage sont complètement accordés aux familles, qui gèrent elles-mêmes les bénéfices de leurs parcelles, (b) soit les parcelles sont gérées collectivement selon des accords votés, (c) soit les parcelles sont partagées au niveau du village par un système de prise d'actions volontaire (Weyerhaeuser et al. 2006). Entre ces trois systèmes, des variantes existent (pondération des voix de vote, coexistence de deux systèmes sur un même village…) et les situations sont très diverses.

On assiste donc dans les années 1980 à un essor des campagnes, grâce à l'élan naturellement commercial et entrepreneur des Chinois. En parallèle, on observe une dérégulation de toutes les instances qui protégeaient les ressources anciennement communes. S'ensuit donc une surexploitation des ressources naturelles. Cependant, la Chine actuelle ne peut se permettre une émigration de masse des ruraux vers les villes. Cette émigration est donc extrêmement contrôlée, et il faut trouver des moyens de produire de la richesse à forte demande en main d'œuvre dans les campagnes (X. Wang et al. 2007).

Les forêts couvraient 25 % de la superficie chinoise en 1950 (frontières de l'époque, en sachant que les territoires annexés par la suite – Tibet - étaient principalement couverts de forêts et de prairies), 98,2 Mha en 1975, 16% en 1988, 66,7 Mha en 1993, et 19,5% en 2008 (JIA Zhibang, directeur de State Forestry Administration, cité par l'agence Xinhua du 9 janvier 2009, dans Villalonga 2009a et Liu 2002, *cf figure i-1a*).

Figure i-1 : Déforestation en Chine et ses risques
a) Evolution de la superficie forestière chinoise (superficie totale de Chine : 960 Mha), sources : Villalonga 2009a, Liu 2002 ; b) Inondations du Fleuve Bleu en 1998, source : Centre canadien de télédétection.



Attention, ces chiffres comprennent les forêts de bambous – environ 2,9 millions ha- et les vergers, les plantations d'hévéas… – environ 4 millions ha. Comment cette remontée est-elle possible ? Il a fallu trois éléments déclencheurs. En 1997, une sévère sécheresse sévit, 267 jours durant, dans le bassin versant du Fleuve Jaune (J. T. Xu & Y. Y. Cao 2001) à tel point qu'aucune goutte du Fleuve n'atteint la mer pendant plusieurs années. L'année suivante, des inondations dévastent le bassin du Fleuve Bleu (Yangtze, cf Figure i-1b) occasionnent plusieurs milliers de décès et plus de 12 milliards US$ de pertes (Lu et al. 2002)). Par ailleurs, le nombre de glissements de terrains ne cessait d'augmenter. Le nombre de morts dues aux glissements de terrain est passé de 278 en 1990 à 1 573 en 1998 (Bobrowsky et al. 2008).

I. 1. c. Programmes chinois de lutte contre les glissements de terrain

Les décideurs chinois sont conscients de la dégradation rapide des terrains et de la nécessité criante de préserver les sols, en particulier sur les pentes. Depuis les années 1970, plusieurs programmes nationaux ont été instaurés en Chine. Parmi eux, les plus importants sont le « suivi et la prévention des glissements de terrain par les masses populaires » (Yin 2008, *encadré ii*), le programme de protection des forêts naturelles (Natural Forest Protection program NFPP, (Weyerhaeuser et al. 2005, Xu et al. 2006, Trac et al. 2007, *encadré iii*) et le programme de conversion des terrains en pente (Sloping Land Conversion Programme SLCP), aussi nommé « Grain for Green project » (Feng et al. 2005, Uchida et al. 2005, *encadré iv*). Le NFPP ne s'applique qu'aux forêts et a pour objectif de conserver les forêts « naturelles », de réduire le volume des coupes dans ces forêts et d'implanter des forêts sur les sols nus et désertiques. Le SLCP quant à lui concerne les surfaces forestières et agricoles qui ont plus de 25° de pente. Il vise à conserver les surfaces déjà en forêts et de convertir les zones agricoles en forêts. Les agriculteurs ont la possibilité de planter des arbres fruitiers, médicinaux ou à des fins de récolte de bois et en compensation ils reçoivent des financements pour acheter et entretenir les jeunes plants et une certaine quantité de riz dépendant de la province (Bennett 2008). De part leurs budgets et les surfaces en jeu, le NFPP et le SLCP sont certainement les plus importants programmes de préservation des forêts par compensation environnementale (« PES » payment for environmental services) jamais connus au monde.

Encadré ii : Inventaire et cartographie des glissements de terrain en Chine

Depuis 1990, dans le cadre de la Décade Internationale pour la Réduction des Catastrophes Naturelles, la Chine a commencé une cartographie des catastrophes naturelles à l'échelle 1 :500 000, qui prend en compte 90 000 catastrophes, dont 55 000 glissements de terrain. En 1999, les enquêtes ont été intensifiées sur des zones à risque pour les glissements de terrain. Ce programme est appelé « Suivi et prévention des glissements de terrain par les masses populaires » car les villageois sont activement impliqués. Le Ministère des Ressources Environnementales a organisé en 2006 des sessions de formation pour les populations rurales. Le programme de ces sessions portait sur les pratiques de construction, les méthodes simples de prévention des glissements de terrain superficiels, l'observation des risques, l'évacuation d'urgence et les premiers secours. 3 millions de villageois ont participé à ces sessions (Yin 2008). Les facteurs susceptibles de provoquer les glissements - précipitations, séismes, activités humaines (en particulier barrages et pipelines) - ont été cartographiés. On en a déduit des cartes de vulnérabilité aux glissements de terrain. Environ 150 000 glissements potentiels ont été identifiés, dont 80 000 sont étroitement suivis. On a également établi des cartes de potentielles pertes matérielles et humaines. Ce

dernier type de cartes est utilisé par les décideurs politiques pour la planification de l'urbanisation et la relocalisation des populations déplacées. En effet, depuis 1999, le Ministère des Ressources Environnementales a publié un acte obligeant à faire une étude d'impact sur les risques de catastrophes naturelles préalablement à toute autorisation de constructions. Cet aspect réglementaire doit être approfondi d'ici 2010, avec la publication de normes-standard techniques d'ici 2010 (Yin 2008).

Bilan : Depuis 1990, on estime que plus de 200 glissements de terrain ont ainsi été stabilisés. L'objectif est que le nombre de glissements de terrain soit diminué de 70% d'ici 2020, les pertes en vies humaines réduites de 1 000 à 300 par an et les pertes matérielles de 10 milliards RMB à 5 milliards RMB par an. Mais il reste beaucoup à faire.

On peut citer l'exemple du célèbre Barrage des Trois Gorges. Ce barrage a accru le risque de pertes par glissements de terrain (a) sur le site même du barrage, par la remontée de l'aquifère, on a créé de nouveaux risques (Chen & Talwani 1998) et exacerbé les risques antérieurs (Highland 2008, Luo & Che 2008) prévoyaint que cette situation empire jusqu'en 2009, date de remplissage maximal du barrage ; et (b) dans les endroits occupés par les populations délocalisées : depuis 1993 et jusqu'en 2009, un total de 1,2 million de personnes vont être délocalisées. Or, dans les environs, la topographie est très abrupte. Les personnes n'ont pas d'autre solution que de s'installer sur des zones instables. Un programme de prévention contre les glissements de terrain autour des Trois Gorges est en cours depuis 2001.

Un autre exemple, récent et tragique, est le tremblement de terre « 5.12 » du 12 mai 2008, à Wenchuan, Sichuan. Ce tremblement de terre a été le plus meurtrier au monde depuis le début du 20ème siècle (quelques chiffres : 69 000 morts confirmées, 375 000 blessés, 19 000 disparus, 4,8 millions de personnes sans logement, 15 millions de personnes vivant sur la zone affectée, qui ont été touchées d'une manière ou d'une autre (Wang et al. 2008, Chigira et al. 2008). Ce tremblement de terre a induit 15 000 catastrophes naturelles (Yin et al. 2008) (glissements de terrain, chutes de pierres, coulées de boues) qui ont occasionné 20 000 morts, soit ¼ du total. Les glissements de terrain ont bloqué le cours des rivières, formant ainsi 256 lacs, dont 32 au moins sont très dangereux car le barrage formé par les débris des glissements est très instable (Cui et al. 2008). Le terrain n'est toujours pas stable et fin 2008, les glissements de terrain attendus étaient classés ainsi : 1% seraient des immenses glissements ($V > 107$ m^3), 9% des glissements importants (107 m^3 > $V > 106$ m^3), 24% des glissements moyens (106 m^3 > $V > 105$ m^3) et 66% des petits glissements ($V < 105$ m^3, Liu 2008). On constate toute l'importance des recherches visant à stabiliser les glissements de terrain superficiels.

Encadré iii : Le NFPP (Natural Forest Protection Programme)

Lancé en 1998, ce programme national consiste en la préservation des forêts déjà existantes par l'interdiction d'abattage dans le Sud-Ouest de la Chine et la mise en place de quotas d'abattage dans le Nord-Est et le reste du pays. Les objectifs affichés sont de conserver 90 millions ha de forêts existantes et de réduire les récoltes de bois de 20 millions m^3 de 1997 à 2003 (production totale de bois en Chine en 1997 : 56 millions m^3). Cette limitation est la plus drastique jamais connue au monde (Xu et al. 2006)

Des plans sociaux ont été déployés pour les employés forestiers et des entreprises forestières des zones touchées, avec l'aide de financements de l'état central, soit pour des pré-retraites, des plans de formation pour faire évoluer les anciens bucherons vers des métiers de pépiniériste ou garde-forestier, ou des délocalisations dans les zones où était mise en place la reforestation des terres agricoles (cf ci-dessous : SLCP). De 1998 à 2010, 14 milliards US$ auront été dépensés pour le NFPP, 80% provenant du gouvernement central, 20% provenant des provinces concernées (communication SFA, 2002). L'apport du gouvernement central a été versé sous forme de subventions aux Bureaux forestiers selon ces montants : 105 €/ha de forêt régénérée et mise en défens auxquels s'ajoutent 1.000 € par employé pour 340 ha de forêt protégée, 75 €/ha replanté par semis aérien, 300 à 450 €/ha replanté manuellement (en fonction de la zone). Ces deux méthodes de semis sont utilisées pour des superficies totales équivalentes (Xu et al. 2006).

Bilan : A ce jour, le bilan du NFPP est plutôt négatif (Brown et al. 2001). La baisse de production de bois est à peine atteinte en 2003 (45 millions m^3) mais peine à se stabiliser. Par ailleurs, elle est compensée par des importations qui ne cessent d'augmenter. Elles ont augmenté de 25 % de 1998 à 2003, pour atteindre plus de 95 millions m^3 d'équivalent bois ronds en 2003 (Sun et al. 2004), bien souvent en provenance de contrats d'exploitation sur des forêts primaires d'Asie du Sud-Est, d'Afrique ou d'Amérique latine, sans compter les importations illégales (Kahrl et al. 2004, Kahrl et al. 2005). Les effets du NFPP sont donc dramatiques pour les pays voisins (Pearce 2001). Le long de la frontière avec le Myanmar on peut voir défiler des camions transportant des grumes fraîchement abattues. Par ailleurs, les provinces ont rarement amené les financements attendus, c'est-à-dire 20% du budget du programme (Liu 2002).

Plus grave, des entreprises forestières ont déposé le bilan, et dans les forêts communautaires qui ont été soumises une interdiction stricte de coupe, les habitants ont perdu une source non négligeable de revenus et de bois de chauffage, qui n'a pas été compensée, contrairement au SLCP. Ce bafouage des droits de propriété des collectifs villageois a été extrêmement mal ressenti par ces derniers, qui, depuis, ne voient plus l'intérêt d'investir des fonds et des efforts dans leur forêt (Yu et al. 2002). L'interdiction totale d'exploitation des forêts a pour conséquence une recrudescence des coupes illégales dans les zones les plus pauvres de la Chine, alors que ces zones était auparavant gérées par des règles traditionnelles de prélèvements réguliers de bois et de produits forestiers non ligneux, « Non-timber forestry products » ou NTFP (Zackey 2007).

Encadré iv : Le SLCP (Sloping Land Conversion Programme)

Lancé en 1999, ce programme, aussi connu sous le nom « Grain For Green », est certainement le plus important (en terme de surface impliquée et certainement en terme de budget alloué) et le plus ambitieux programme PES jamais connu au monde. Il consiste en la conversion de terres agricoles en forêts, et particulièrement sur les pentes de plus de 25°. Cet objectif devait être atteint en 2010. La phase pilote de ce programme a été menée de 1999 à 2001 (1,2 millions ha convertis), puis a été lancée la phase opérationnelle. En 2007, l'objectif étant quasiment atteint, un nouveau programme a été annoncé, pour une nouvelle période de 8 ans à partir de 2010 (State Council of the PRC 2007).
A terme, ce sont donc 15 millions d'hectares de terres agricoles qui sont susceptibles d'être convertis en forêts, dont 1/3 sur des pentes de plus de 25°. Un objectif moins affiché est de convertir la même superficie de « friches » en forêt. Cela représentera pour la Chine une augmentation de 10 à 20% de sa surface forestière (167 millions ha), en contrepartie d'une perte d'au moins 10% de sa superficie agricole (Hyde et al. 2003). N'oublions pas que la Chine actuellement doit nourrir 20% de la population mondiale avec 7% des terres arables du monde. Un Chinois dispose en moyenne de 0,1 ha de terres arables, alors que la moyenne mondiale est estimée à 0,2 ha et 0,5 ha en France (FAO 2007). 75% des parcelles doivent être plantées en « forêt écologique » (appellation trompeuse car il s'agit en fait de plantations pour le bois de grume), et sur 25 % sont autorisées des plantations en vergers, ou arbres médicinaux. Parfois, la prairie permanente est autorisée. Le statut de l'agroforesterie combinant des cultures annuelles avec des arbres pérennes (« intercropping ») n'est pas clair. Selon certains auteurs (He et al. 2009), l'agroforesterie ne serait pas permise sur les parcelles engagées. Le cas des arbustes fruitiers ou médicinaux n'est pas clair non plus. Les agriculteurs sont autorisés à récolter les produits de ces plantations.
Ce programme affiche un budget global de plus de 40 milliards US$ (Tao et al. 2004). En effet, les agriculteurs reçoivent 1,50 à 2,55 tonnes de riz/an/ha engagé (en fonction des zones), d'où l'appellation « Grain for green », le prix du riz pouvant être approximativement estimé à 140 €/tonne. Ils reçoivent également, pour les dépenses d'entretien, 30 €/an/ha engagé. Les terres plantées en « forêts écologiques » sont compensées pendant 8 ans, les terres plantées en « vergers » sont compensées pendant 5 ans et les prairies pendant 2 ans. De plus, au début de leur contrat SLCP, les agriculteurs reçoivent 75 €/ha pour acheter les semis ou les jeunes plants. Par ailleurs, les parcelles reforestées sont exemptes de taxes agricoles. Ces montants sont à comparer au revenu moyen de l'agriculteur chinois, estimé à 300 €/an (avec de fortes disparités régionales bien entendu). Les bureaux forestiers sont également rémunérés. En 2006, 15 millions de foyers étaient engagés, pour 9 millions ha replantés. On estime qu'à terme jusque 60 millions de foyers peuvent être impliqués.
Bilan : Dix ans après la mise en place du SLCP, les premières parcelles engagées dans le programme ont atteint la fin de leur contrat, et les premiers bilans (rédigés par des Chinois comme par des étrangers) de cette opération de vaste ampleur sont publiés. En terme de superficies converties en forêts, 9 millions ha étaient convertis en 2005, et le rythme s'accélère, puisque pendant la seule année 2008 4,7 millions ha ont été reboisés, et selon Hui Langyu, vice-premier ministre chinois, on prévoit 5,48 millions ha de reboisement en 2009 (dont 2,5 millions par des bénévoles, Agence Xinhua, 9 janvier 2009). A la lumière de ces chiffres, on comprend que (a) le SLCP dépasse toutes les attentes, (b) le SLCP a donné l'impulsion à des programmes de reboisement parallèles (en particulier les programmes de lutte contre la désertification dans le nord de la Chine et (c) les taux de reprise des semis et jeunes plants ont été médiocres, ce qui amène à devoir replanter, une même superficie étant donc comptabilisée à plusieurs reprises. En général, les foyers s'estiment satisfaits de la démarche, car leurs revenus sont largement compensés, le riz offert dépassant souvent les rendements précédents. Ceci est vrai dans la plupart des cas, mais dans certaines zones on déplore la mauvaise qualité du riz livré, les délais de livraison (surtout ces dernières années), la corruption des agences forestières locales. Par ailleurs, ceci n'était pas vrai pour les foyers élevant du bétail. En effet, pour ceux-ci, il demeurait plus intéressant de continuer à produire du maïs pour leur bétail (le riz acquis par le SLCP ne peut être ni échangé ni vendu). Et lorsque l'on compare l'augmentation des revenus des agriculteurs engagés avec celle des autres foyers, on constate que les revenus « hors agriculture » permettent souvent d'augmenter bien plus considérablement les revenus que le SLCP. Or, même s'il l'on pourrait croire que ce sont les agriculteurs dont le travail agricole est allégé par le SLCP qui se tournent davantage vers des activités « off-farm », dans les faits, ceci n'est pas aussi clair (Xu et al. 2006). Les agriculteurs ayant planté des forêts « écologiques » espèrent beaucoup des produits de leurs parcelles dans quelques années. Mais ils craignent que les compensations ne durent pas le temps de l'engagement initial, et même au-delà (8 ans pour les arbres de bois d'œuvre, 5 ans pour les vergers), ils craignent que leurs arbres ne soient pas matures pour prendre le relai des compensations financières. Le régime foncier en Chine reste très instable : les agriculteurs détiennent un droit d'usage mais ne sont pas individuellement propriétaires de leurs parcelles. Selon les zones et le respect ou non de ce droit d'usage, les agriculteurs sont plus ou moins enclins à investir sur de longues périodes sur les parcelles qu'on leur a allouées. Les foyers interrogés dans différentes études indiquent qu'ils étaient volontaires pour participer au programme (Weyerhaeuser et al. 2005b). Par contre, ils n'ont pas eu le choix des parcelles ni de la superficie à engager. Ils n'ont pas pu choisir non plus les espèces à planter. En effet, les agences forestières locales préfèrent suivre et contrôler de grandes parcelles monospécifiques. Les espèces ont été imposées sans étude de marché préalable. Les agriculteurs déplorent également le fait qu'ils n'ont pas bénéficié de suffisamment d'aide et de conseils techniques dans l'entretien de leurs plantations. Le risque en ne responsabilisant pas suffisamment les agriculteurs est d'engendrer un désengagement et un manque d'entretien des parcelles (Xu & Cao 2001). Les agences forestières locales se disent complètement dépassées par les missions qui leur ont été confiées (Weyerhaeuser et al. 2005b). Le nombre de forestiers chinois est passé de 55.000 à

187.000 employés en 2002. En particulier, les anciens bûcherons au chômage à cause du NFPP ont été réorientés dans le cadre du SLCP. Ils ont donc sensiblement changé de métier et élargi leurs domaines d'action. Plus largement, en décembre dernier, Jia Zhibang, directeur de la SFA, a annoncé la création de 36 millions d'emplois dans les secteurs de la forêt, mais aussi du tourisme « environnemental », de la gestion cynégétique et piscicole, des arbres médicinaux et d'ornement (China Daily 23/12/2008). Dans les faits, les forestiers sont souvent d'anciens bucherons, employés, voire soldats, et la plupart n'ont pas suivi de formation dans la mise en place de politiques forestières locales et intégrées comme le SLCP. Il en résulte un suivi très léger du programme, et des contrôles inefficaces. A cause du NFPP, les agences forestières locales ont perdu la plupart de leurs financements propres. Une façon de compenser cette perte est de vendre des jeunes plants pour le SLCP. C'est pourquoi elles se concentrent sur une petite sélection d'espèces bien connues (par exemple les pins, les poiriers, les noyers, et autres espèces qui germent rapidement). D'un point de vue économique, le SLCP a amené des distorsions au niveau local sur le prix des matières premières. Au niveau international également, le retrait de terres agricoles en Chine pèse sur le marché mondial. La Chine fait face à un pesant problème de sécurité alimentaire. Monter des politiques d'une telle ampleur sur de si longues périodes amène inévitablement des incertitudes sur l'estimation du budget à prévoir. Les années passant, le SLCP est victime de son succès, les bénéficiaires de plus en plus nombreux et les coûts de plus en plus élevés. D'un point de vue environnemental, les effets doivent être étudiés avec attention. Les taux de survie des arbres varient d'une région à l'autre, on parle de 30% dans le nord-ouest de la Chine, et même seulement 10% sur le Plateau de Loess (Wang et al. 2007). Les bureaux forestiers imputent cela au fait que 75€/ha ne sont pas suffisant pour acheter des plants de bonne qualité (Weyerhaeuser et al. 2005b). Le reboisement n'a pas été conçu en fonction des spécificités locales, on a souvent planté des arbres exotiques au lieu de restaurer la végétation originelle. Par exemple, au lieu de planter des arbres, le SLCP ne paie pas assez attention aux prairies dans les zones sèches et arides (Xu et al. 2006). Afin de corriger ces écarts, un programme séparé, coordonné par le Ministère de l'Agriculture, a été doté de 2 milliards € pour restaurer les prairies de l'ouest de la Chine sur la période 2003-2007. Ce programme sort du sujet de ce rapport, mais on pourrait aussi en étudier les conséquences. Plus regrettable, le SLCP n'a été couplé à aucun programme de gestion des eaux, développement agricole, ou d'aménagement territorial de la même ampleur. C'est ainsi qu'on continue de voir se développer de façon non réfléchie barrages, pistes, cultures intensives sur zones critiques. C'est la SFA qui est en charge de l'application du NFPP et du SLCP, mais elle n'a aucun compte à rendre aux autres agences ou ministères en charge de l'agriculture, de l'élevage, de la protection de l'environnement, de la conservation des eaux et des sols, ou des aspects sociaux.

Le bilan du SLCP est donc aussi mitigé, plutôt positif à l'heure actuelle, mais lourd d'incertitudes pour la suite. Le gouvernement central est donc actuellement dans une situation où il doit absolument éviter que les paysans déboisent leurs parcelles engagées pour en récupérer la surface agricole. Si la compensation environnementale ne devait pas continuer, ce sont 1/5 à 1/3 des terres reboisées qui retourneraient en terres agricoles (Bennett 2008). Mais par ailleurs le gouvernement central hésite à continuer de dépenser des sommes si importantes pour la compensation financière des agriculteurs. Ou du moins, s'il décide de continuer, c'est dans le cadre d'une politique agricole et forestière intégrée qui doit contribuer également au développement économique des campagnes.

Les bilans du NFPP et du SLCP sont mitigés (*Encadrés iii et iv*). Dans certains cas précis les espèces replantées n'étaient pas adaptées, entrainant une mortalité élevée des jeunes plants (Weyerhaeuser et al. 2005), dans d'autres cas la végétation de sous-bois a été enlevée ou ne pouvait pousser à l'ombre des arbres nouvellement plantés (Genet et al. 2008, Fattet et al. 2011). Ces pratiques ont parfois eu comme conséquence la réduction de la diversité des espèces (Cao et al. 2009), la dégradation du bien-être des populations locales (Xu et al. 2006, Xu et al. 2004, Xu & Cao 2001), la recrudescence de l'érosion de surface (Fattet et al. 2010) et diminution de la stabilité des pentes (Genet et al. 2008). Dans ce contexte, les politiques de reforestation doivent tenir compte de l'écologie locale et des besoins des populations locales avant de faire le choix des espèces à replanter, par exemple on devrait faire appel aux connaissances ethnobotaniques afin que les espèces retenues puissent procurer à la fois des services écosystémiques tels que la prévention des glissements de terrain ainsi que des revenus pour les populations locales (Grosjean & Kontoleon 2009). L'étendue du SLCP en elle-même fait que l'observation de ce programme PES est des plus intéressantes. Dans le but de concevoir la deuxième phase annoncée du SLCP, de 2010 à 2018, le gouvernement chinois a prévu d'améliorer les modalités de mises en œuvre de ce programme.

Les orientations suivantes sont avancées :

(1) Les communautés locales pourraient avoir davantage de droit à la parole dans la conception du programme, dans le choix des espèces et des parcelles (Bennett 2008) ;

(2) Il faut améliorer le soutien technique apporté aux agriculteurs ;

(3) L'accent doit donc être mis sur la formation des forestiers ;

(4) Il est nécessaire d'éclaircir le régime foncier chinois, de protéger les droits de propriété individuelle et les droits d'usage des terres sur le long terme et enfin de faciliter les échanges de biens tels que le fermage, la location, l'achat et la vente de terres agricoles ou forestières (Grosjean & Kontoleon 2009) ;

(4) Il faut admettre que le SLCP n'est pas tant un programme environnemental qu'un programme social de diminution de la pauvreté dans les campagnes et les montagnes. Ca n'est pas un mal en soi, mais il faut donc redéfinir des objectifs environnementaux clairs pour ce programme, et l'accompagner d'une véritable politique agricole, forestière et de développement rural (développement des filières, des crédits d'investissement, des techniques agricoles, de la valeur ajoutée locale, désenclavement des marchés, sécurité sociale, éducation) ;

(5) L'état chinois, aussi riche soit-il, et surtout dans le contexte économique mondial que l'on connaît, doit trouver des alternatives au financement de tels programmes. La participation des provinces ou de capitaux privés locaux sont des pistes envisageables.

Le cas de la Chine est intéressant car il reprend, de façon exacerbée, des problématiques connues en France et dans d'autres pays où la recherche française est davantage présente : restauration des terrains de montagne, compétition pour les terrains agricoles au détriment de terrains forestiers, urgence d'action. Par ailleurs, les mouvements tectoniques toujours actifs de nos jours en Chine mettent à disposition des espèces végétales dont les stratégies d'enracinement ont été influencées par une instabilité permanente.

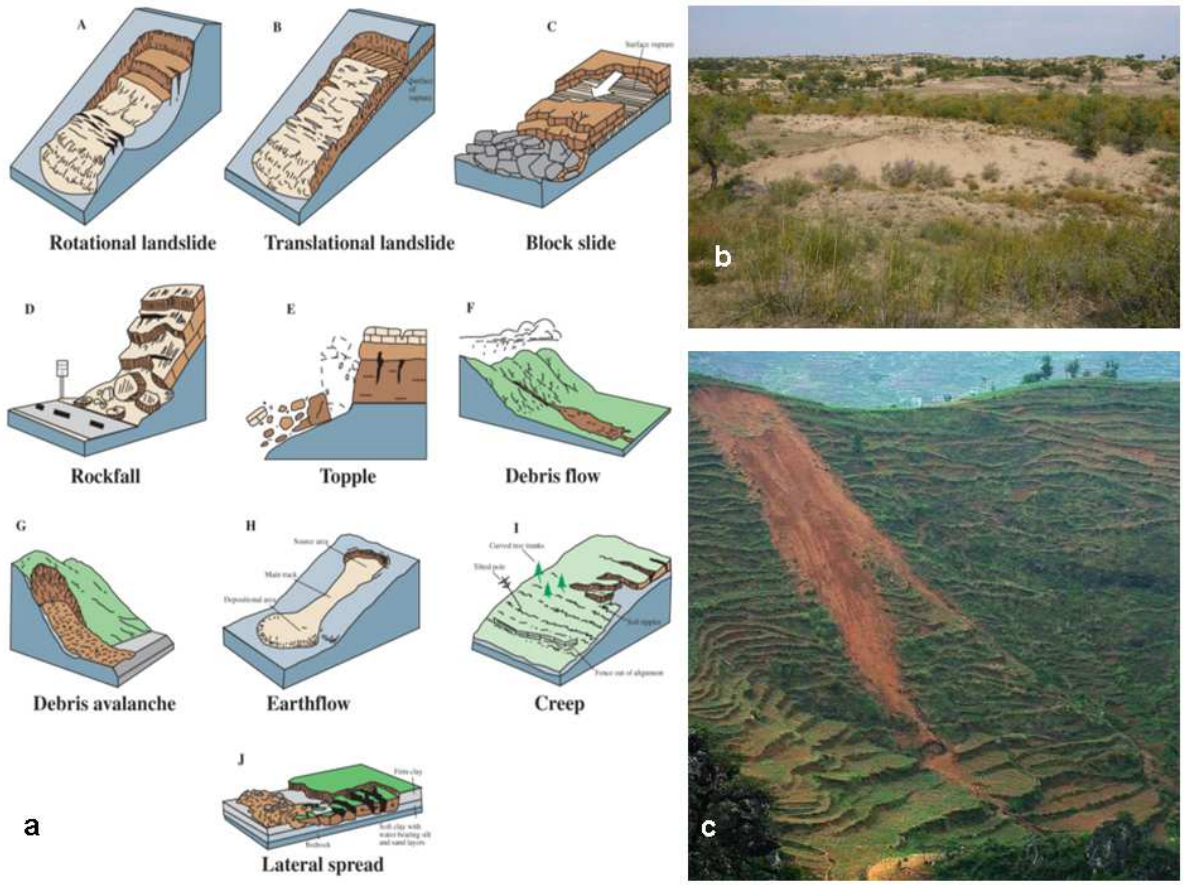
La thèse se place donc dans le cadre sociologique et politique de la Chine et géographique des contreforts himalayens en particulier. Le périmètre est donc de proposer des préconisations qui répondent au moins en partie aux attentes des Chinois pour contrer certains glissements de terrain : solutions peu coûteuses demandant peu de connaissances techniques, intégrant des espèces végétales économiquement intéressantes pour les populations locales, si possible natives de la zone géographique.

I. 2. L'éco-ingénierie des glissements de terrain, débat scientifique en vigueur

I. 2. a. Ce que sont et ce que ne sont pas les glissements de terrain

Les glissements de terrain sont définis comme le mouvement en masse vers le bas ou vers l'extérieur de matériaux provenant d'une pente, composés de roche, de sol, de remblais artificiel ou d'une combinaison de ces matériaux. La gravité est le premier facteur déclenchant, même s'il peut être aggravé par les effets de l'eau (Sidle & Ochiai 2006). Ce qu'on appelle communément « glissements de terrain » revêt donc en réalité une large gamme de phénomènes (*Figure 1a*)

Figure 1 : Glissements de terrain et érosion
a) Les types de glissement de terrain les plus fréquents, source : USGS ; b) Dans les dunes de sable de la Chine du Nord, le surpâturage et la déforestation ont pour conséquence une érosion éolienne de plus en plus intense, photo : M. Ghestem ; c) Depuis les 50 dernières années en Chine septentrionale, les forêts naturelles ont été abattues et remplacées par des cultures. La piètre fixation du sol par des espèces inadéquates peut engendrer des glissements de terrain, photo : T. Fourcaud.



Une définition plus restreinte des glissements de terrain avait été proposée par Varnes (1978) : les glissements de terrain sont un type de rupture d'une pente caractérisée par le mouvement rapide du sol et/ou des roches sur une surface de cisaillement. Cette définition ne comprenait que les mouvements de masse rapides et excluait donc les mouvements lents (« creeps », *Figure 1a I*).
Les glissements de terrain se distinguent de l'érosion des sols, qui est un phénomène de surface (*Figure 1b*). L'érosion peut être causée par l'abrasion du vent, de l'eau, des différences de température et d'humidité ou par des facteurs mécaniques tels que le passage d'engins ou d'animaux. Sous l'effet de ces facteurs, les agrégats du sol se désagrègent en particules plus fines et plus mobiles. Cette désagrégation diminue l'infiltration de l'eau dans le sol, augmente le ruissellement, la formation d'une croûte de surface et la formation de rigoles (Legout et al. 2005, Martı́nez-Mena et al. 1999). La stabilité des agrégats dans les horizons de surface du sol est donc la propriété pédologique principale qui permet d'expliquer, de quantifier et de prédire les processus d'érosion (Le Bissonnais et al. 2007, Barthès & Roose 2002), alors que pour les glissements de terrain on s'intéressera aux valeurs de la cohésion interne et de l'angle de frottement interne de la masse de sol (Magnan 1991). Cette thèse ne s'attarde pas sur l'étude de l'érosion des sols, même si un travail mené en collaboration a permis de montrer que les processus guidant l'érosion et les glissements de terrain sont liés.

► Fattet, Yun, Ghestem, Ma, Foulonneau, Nespoulos, Le Bissonnais, Stokes. 2011. Effects of vegetation type on soil resistance to erosion: Relationship between aggregate stability and shear strength. Catena 87: 60-69. doi: 10.1016/j.catena.2011.05.006

I. 2. b. Qu'est-ce que l'éco-ingénierie, l'éco-ingénierie des pentes ?

► Stokes, Sotir, Cheng, Ghestem. 2010. Soil bio- and eco-engineering in China: Past experience and future priorities. Ecological Engineering 36: 247-257. doi:10.1016/j.ecoleng.2009.07.008

L'activité humaine, dans les 100 dernières années, a connu une productivité croissante grâce à de considérables progrès technologiques, mais au prix de la dégradation de l'environnement (Painter 2003). Il est maintenant nécessaire de réparer ces dommages. Cependant, certains pays aux ressources limitées ne peuvent pas se permettre d'investir lourdement dans la restauration de leurs sites dégradés. La première mise en pratique, la bio-ingénierie intègre les techniques du génie civil et l'utilisation de matériaux naturels ou conçus par l'Homme pour obtenir des méthodes de protection et de restauration rapides, efficaces sur le court-terme et économiques (Schiechtl 1980, Coppin & Richards 1990). Traditionnellement les géotechniciens en charge de rechercher des solutions pour faire face à des risques naturels construisent des ouvrages artificiels ou bien utilisent des géotextiles. La mise en place de petites terrasses, la plantation d'herbacées à croissance rapide, *e.g. Vetiveria zizanioides* sont des techniques typiques de la bio-ingénierie des sols. L'ingénierie écologique, émanant d'une réflexion plus globale, a été décrite comme « la gestion de la nature » (Odum 2007) ou comme « la conception d'écosystèmes durables qui intègrent la société humaine et son environnement naturel, pour le bénéfice de ces deux parties » (Mitsch & Jørgensen 2004, David 2003, Mitsch 1996). L'ingénierie écologique a été largement appliquée aux zones humides, aux eaux usées et à l'aquaculture, mais peut être appliquée à d'autres milieux. Plus récemment, le terme « éco-ingénierie » a été défini comme « la stratégie pour gérer un site de façon écologique et sur le long-terme, en tenant compte des aléas naturels et anthropiques » (Stokes et al. 2004). L'éco-ingénierie est donc plus pratique et appliquée que l'ingénierie écologique et considère davantage le long-terme que la bio-ingénierie. Les techniques d'éco-ingénierie adaptées à des pentes permettent d'obtenir des solutions efficaces destinées à protéger et maintenir l'environnement menacé (Gray & Sotir 1996, Coppin & Richards 1990). Ces méthodes d'éco-ingénierie présentent, par ailleurs, l'avantage d'être esthétiques, de concilier les besoins de sécurisation des pentes à des soucis d'aménagement de l'environnement et de conservation de la biodiversité. Des stratégies de gestion sont ensuite proposées pour conserver le site (*Figure 2a et b*).

Figure 2 : Eco-ingénierie
a) L'éco-ingénierie inclut la gestion des forêts de protection pour réduire les éboulis dans les Alpes françaises, photo : A. Stokes ; b) De nouvelles méthodes d'éco-ingénierie aident à réduire les pertes de sol sur les pentes raides. Sur des tests dans la province du Sichuan, des haies ont été plantées avec une association de pêchers (*Pyrus* spp.) et de lys (*Hemerocallis citrina* Baroni). Par cette technique, la perte de sol a été réduite de 80% (Stokes et al. 2007), photo : Chen ; c) Les trois types principaux d'architecture racinaire : en haut : le système « cœur » (heart), au milieu : le système « plaque » (plate) et en bas : le système « pivot » (tap, d'après Stokes & Mattheck 1996a, Köstler et al. 1968).

Les glissements de terrain se déclenchent lorsque les forces qui déstabilisent la pente deviennent plus importantes que les forces qui la stabilisent (Cornforth 2005). La végétation peut participer à l'augmentation des forces qui stabilisent les pentes, au travers de processus hydriques et mécaniques. Ce rôle peut être négatif ou positif pour la stabilité (*Tableau 1*).

Tableau 1: Impacts de la végétation sur la stabilité des pentes
Effet N: négatif, B: bénéfique, m: marginal, adapté de Greenway (1987) et Sidle & Ochiai (2006).

Processus affectant la stabilité des pentes et leur influence sur:	les glissements de terrain rapides et superficiels	les glissements de terrain plus profonds
Processus hydriques		
H1. Interception des précipitations par la canopée	mB	mB
H2. Augmentation de la rugosité de surface par la litière organique, apparition du « biomat flow », flux d'eau au sein de la litière organique (R. Sidle et al. 2007)	mN (B pour l'érosion)	mN
H3. Action des racines comme "preferential flow paths", chemins préférentiels pour l'écoulement de l'eau	B / N	B / N
H4. Extraction de l'eau hors du sol par les racines	B / mN	B / mN
Processus mécaniques		
M1. Renforcement par les racines fines comme des fibres dans la matrice sol	B	B
M2. Ancrage des zones fragiles à des zones plus solides et au substrat rocheux plus stable par les racines rigides	B	mB
M3. Augmentation de la force normale et de la force parallèle à la surface du sol par le poids des arbres	mB / mN	mB / mN
M4. Transmission des forces dynamiques du vent dans le sol via le tronc et les racines	mN	mN

Les processus impliquant la partie épigée des plantes influencent moins la stabilité des pentes que les processus impliquant les racines. Pour que les végétaux aient un réel impact sur les glissements de terrain, il faut que leurs racines traversent la zone potentielle de cisaillement. Il est illusoire d'espérer empêcher tous les glissements de terrain uniquement avec l'action des plantes. C'est pourquoi cette thèse ne s'intéresse qu'aux glissements de terrain superficiels. Par contre, l'utilisation de la végétation se justifie quelque que soit la forme de la zone potentielle de cisaillement : en loupe ou parallèle à la surface du sol (*Figure 1a A et B*) et quelque que soit la vitesse de glissement, qu'elle soit rapide (*Figure 1a A et B*) ou lente (*Figure 1a I*).
Les processus qui ont pour conséquence une diminution de la pression hydrostatique dans le sol sont bénéfiques alors que ceux qui l'augmentent sont négatifs. En ce qui concerne les processus mécaniques, ceux qui augmentent la résistance au cisaillement du sol sont bénéfiques alors que ceux qui augmentent la contrainte de cisaillement dans le sol sont négatifs (Greenway 1987).

I. 2. c. Le rôle des racines à l'interface entre la mécanique, l'architecture et l'hydrologie

Le rôle stabilisateur des racines dans les pentes n'est pas une idée nouvelle. On a trouvé des preuves de l'utilisation des plantes pour la stabilisation des sols datant de la Chine des Hans, en 28 avant JC (Redfield 2000), de l'Athènes de Sophocle et de la Rome de Pline (Stokes et al. 2004), jusqu'à la République de Venise au XIIème siècle. Ensuite viennent le programme RTM (Restauration des terrains de montagne) sous Napoléon III en France et ses pendants de l'autre côté des frontières alpines : Wildbach und Lawinenverbauung, en Autriche et en Allemagne, et Sistemazioni idraulico-forestali en Italie (Bischetti et al. 2009).

D'un point de vue mécanique, il existe plusieurs formes de dissipation de l'énergie gravitaire dans un sol contenant des racines :

(1) Rupture du continuum sol : elle dépend des seules propriétés mécaniques du sol ;

(2) Rupture du contact sol-racine : la racine glisse dans le sol. La force de friction sol-racine est souvent considérée comme très forte, et donc peu importante dans l'étude des phénomènes de glissement de terrain car on considère que ça n'est pas là que le glissement commence (Schmidt et al. 2001). Cependant, d'autres auteurs (Pollen 2007) estiment que ce mode de rupture n'est pas négligeable ;

(3) Rupture du contact bois-cortex à l'intérieur de la racine, au niveau du cambium : la racine glisse dans son écorce. On observe souvent ce phénomène au niveau des surfaces de glissement à nu. Cependant, en aval sur la racine, c'est quand même bien souvent le bois qui a cassé ; on retrouve donc le phénomène (4) ci-dessous ;

(4) Déformation puis rupture de la racine elle-même : cette rupture est souvent assimilée à une rupture fragile (subite), alors que l'aspect tortueux, élastique et plastique de la racine joue certainement un grand rôle. Elle dépend des propriétés mécaniques des racines (résistance à la mise en tension, résistance à la flexion, *cf* ci-après).

Afin de prendre en compte à la fois le sol et les racines, on peut s'inspirer de la théorie du sol renforcé (Vidal 1969) qui décrit les fibres introduites dans une masse de sol comme des éléments qui augmentent la résistance au cisaillement du sol par l'augmentation de sa cohésion apparente. Les racines elles-mêmes sont considérées comme des matériaux avec des propriétés mécaniques propres. Cependant, les racines ne sont pas statiques, il faut donc affiner cette analyse mécanique avec des processus biologiques et écologiques tels que la croissance et la survie des racines dans le milieu sol.

La biomécanique est une discipline qui étudie les propriétés mécaniques des matériaux vivants. L'architecture des plantes (architecture aérienne et architecture racinaire) est une approche originale qui est définie comme la nature et la position relative des différents axes qui constituent une plante ou un système racinaire. Elle résulte du fonctionnement des méristèmes apicaux (Hallé & Oldeman 1970). Elle est, à tout moment, l'expression d'un équilibre entre des processus endogènes de croissance et des contraintes extérieures exercées par le milieu (Edelin 1984). C'est une approche qui permet de comprendre la construction progressive, ou l'ontogénie, des végétaux dans le temps et dans l'espace en considérant la plante comme un organisme modulaire composé de plusieurs unités qui s'agencent les unes par rapport aux autres (Barthélémy & Caraglio 2007). Le terme « architecture » d'une plante désigne donc à la fois des caractéristiques propres à cette plante (morphologie, ontogénie…) et une méthode d'étude. L'architecture racinaire est le parent pauvre de l'architecture des plantes, à cause de la difficulté d'observation des racines. Elle se décompose en deux domaines : la géographie (étude de la forme = morphologie, de la taille, de l'orientation…) et la topologie (étude des connections des axes) (Danjon & Reubens 2008). Les premiers stades de développement du système racinaire sont largement sous contrôle génétique (Stokes et al. 2009). Il est courant de regrouper les systèmes racinaires selon de larges catégories (Köstler et al. 1968, *figure 2c*) : les systèmes « cœur » caractérisé par un ensemble dense de racines plus fines et orientées dans toutes les directions, les systèmes « plaque » ou traçants dont les racines se développent à l'horizontale en surface, et enfin les systèmes « pivot » constitués d'une grosse racine verticale, appelée pivot, se développant dans le prolongement du tronc et de racines latérales partant du collet. Cependant ces catégories ne sont pas illustratives de telle ou telle espèce car la plupart des espèces peuvent présenter un mélange de ces types de morphologie et également changer de morphologie au cours de leur vie (Puhe 2003, Raimbault 2001, Atger & Edelin

1994). Il a été montré que les plantes adaptent leur système racinaire aux conditions de forte pente de façon dissymétrique (Khuder 2006, Chiatante et al. 2003, Noguchi et al. 1997b) et ce dès les premiers stades de développement des racines (Khuder et al. 2007). Afin de décrire précisément voire quantitativement l'architecture d'un système racinaire, il existe un large panel de paramètres architecturaux observables et mesurables, et différentes méthodes (voir Danjon & Reubens 2008 pour une review).

Les premiers à véritablement poser des méthodes de calcul (modèle analogique, équations) de la stabilité additionnelle apportée par les racines sont Waldron (1977) et Wu et al. (1979). Ces derniers parviennent à une équation relativement simple, qui indique que la cohésion additionnelle apportée par les racines au sol dépend uniquement de la quantité de racines dans le sol et de leur résistance à la tension :

$$Cr = 1{,}2 * Tr * RAR \qquad \textit{équation 1}$$

avec Tr : résistance des racines à la rupture en tension, Cr : cohésion additionnelle apportée par les racines, et RAR (root area ratio) : surface totale de racines interceptées par unité de surface de sol au niveau de la surface de glissement. (Pour la démonstration, voir Wu et al. 1979). Ce modèle repose donc sur la seule connaissance d'une donnée biomécanique, Tr et d'une donnée d'architecture racinaire, RAR. Le modèle de Waldron et Wu (ensuite nommé W&W's dans ce rapport) a été affiné et utilisé par de nombreux chercheurs. Cependant, depuis une dizaine d'années, des travaux, dont celui effectué par Wu lui-même (Wu & Watson 1998) le remettent en cause. En effet, ce modèle surestimerait jusqu'à 200% la cohésion additionnelle réellement apportée par les racines, ce qui est très délicat dans le cadre de la prévention de risques de glissements de terrain (Mao et al. 2011, Schwarz et al. 2010a & b, Bischetti et al. 2009, Docker & Hubble 2008, Pollen & Simon 2005, Waldron & Dakessian 1981). Pollen & Simon (2005) et Thomas & Pollen-Bankhead (2010) proposent un modèle numérique itératif (RipRoot) estimant l'erreur introduite par le modèle de Wu, basé sur le concept du faisceau de fibres (FBM, Fiber Bundle Model) qui cassent progressivement. Lorsqu'une racine casse, la contrainte qui était supportée par la racine cassée est redistribuée sur les autres racines. Le FBM le plus simple (GLS : global load sharing) formule l'hypothèse que la contrainte restante est redistribuée sur les n-1 racines restantes en fonction de leur diamètre. Une alternative est le FBM-LLS (local load sharing), dans lequel la contrainte restante est redistribuée préférentiellement sur les racines les plus proches de la racine qui vient de rompre. Hidalgo et al. (2002) estiment que dans un milieu assez homogène, les phénomènes réels sont intermédiaires entre le GLS et le LLS : la concentration de la contrainte est plus importante aux alentours de l'endroit de rupture, mais dans une certaine mesure elle se propage à toute la matrice. Il demeure des hypothèses fortes dans les FBM : on suppose que toutes les racines présentent les mêmes propriétés élastiques et qu'elles sont toutes perpendiculaires à la zone de glissement. Mais ils peuvent être affinés, par exemple on a étudié l'aspect dynamique de la déformation : on a ajouté aux FBM des modèles dépendants du temps dans lesquels les racines cassent après avoir été soumises à une contrainte pendant un certain temps. On peut aussi ajouter des modèles qui tiennent compte de la non-linéarité des comportements mécaniques des fibres (Scwharz et al. 2010b, Moral et al. 2001). Il permet également plus simplement d'affecter aux équations du modèle W&W's un coefficient correcteur k''<1 dépendant de caractères biologiques de la plante tels que le nombre de racines et la gamme de diamètres des racines (Bischetti et al. 2009).

La comparaison entre le modèle W&W's et les réflexions apportées par les avancées sur le FBM est une bonne porte d'entrée pour présenter les points soumis à discussion dans l'état actuel de la recherche (Tableau 2). Ces points portent sur l'approfondissement nécessaire des connaissances en biomécanique et en architecture des systèmes racinaires, mais également sur la prise en compte de l'état hydrique du sol et des interactions hydriques sol-racines lors du déclenchement du glissement de

terrain. L'eau réside à la fois dans le sol matriciel constituée de la porosité fine où l'eau transite par des flux uniformes, saturés ou non saturés, mais également dans les pores plus importants dans lesquelles elle transite par des flux non-uniformes. Ces flux sont assez bien connus dans le cas d'ouvrages d'art sur les cours d'eau tels que digues et barrages (Zanetti et al. 2010) à cause des risques qu'ils engendrent sur la solidité de ces ouvrages et commencent à être étudiés en association avec des risques gravitaires dans le cas de ripisylves en pente (Pollen 2007, Simon & Collison 2002). De fait, l'apparition de zones de surpression hydrique et de « renards » (voies d'eau) ne concerne pas uniquement les sols en bordure de cours d'eau mais tous les sols traversés par des racines, et le risque est accru lorsque le sol est en pente. L'augmentation des risques de glissement de terrain à cause de la surpression hydrique dans les pentes a été observée à différentes reprises (Uchida et al. 2005, Uchida et al. 2001, Noguchi et al. 1997a, Tsuboyama et al. 1994, Tsukamoto 1987, Pierson 1983, Gaiser 1952), mais la conceptualisation et la quantification des phénomènes en relation avec la présence de racines sur des fortes pentes ne se développent que depuis une décennie, en particulier avec l'apparition des concepts de « preferential flow paths » et « biomat flow »(Nieber & Sidle 2010, Sidle et al. 2007, Sidle et al. 2001, Sidle et al. 2000). Actuellement, les effets mécaniques des racines sur les fortes pentes sont fortement remis en question par l'étude de ces effets hydriques, qui peuvent être bénéfiques mais aussi dangereusement négatifs selon les conditions climatiques du milieu.

Cette thèse a pour périmètre l'étude des glissements de terrain que la présence de végétation peut éviter, c'est-à-dire les glissements de terrain superficiels dont la zone de glissement se situe à moins de 2 m de profondeur. Elle s'intéressera à la fois aux phénomènes hydriques et mécaniques qui ont lieu entre le sol et les racines.

Tableau 2 : Présentation des hypothèses du modèle W&W's et remise en cause

Domaine scientifique	Hypothèses posées par le modèle W&W's	Hypothèse contradictoire
Biomécanique	(1) toutes les racines cassent simultanément	Sauf sous certaines conditions de pluie soudaine (mousson) ou de déplacement rapide de flux de sédiments, les racines ne cassent pas simultanément (Schmidt et al. 2001). La résistance maximale n'est pas la seule propriété à prendre en compte pour décrire le comportement d'une racine en tension, il faut aussi tenir compte de sa capacité à se déformer (Schwarz et al. 2010a, Norris 2005).
Architecture	(2) la déformation du sol en cisaillement est confinée à une zone mince. On suppose donc qu'il ne se passe rien au-dessus et en-dessous de la zone de cisaillement. Cette hypothèse illustre par exemple le cas où le glissement de terrain a lieu à l'exacte interface entre le sol meuble et la roche-mère compacte	Si la zone de déformation due au cisaillement est épaisse, les phénomènes sont plus complexes, les racines et ramifications au-dessus et en-dessous du plan de cisaillement sont mobilisées et peuvent avoir un effet, comme il a été montré pour des plantes arrachées ou soumises à des tempêtes (Burylo et al. 2009, Mickovski et al. 2007, Mickovski et al. 2007, Dupuy et al. 2007, Dupuy et al. 2005a, b et c, Stokes et al. 1996, Stokes & Mattheck 1996b)
Biomécanique	(3) (cette hypothèse est un corollaire de la précédente) toutes les racines sont flexibles et n'opposent pas de résistance à la flexion. On ne tient pas compte du phénomène de résistance à la flexion des racines = on néglige les moments fléchissants (bending moments) et le flambage en compression des racines orientées vers le bas de la pente (buckling).	Quand la zone de déformation due au cisaillement est épaisse, les racines fléchissent. Il est possible de calculer cette résistance à la flexion en prenant en compte le module en flexion, qui permet de calculer le moment d'inertie dans des équations de solution pour la flexion d'un câble ou d'un pieu (Wu & Watson 1998).
Biomécanique	(4) (cette hypothèse est un corollaire de la 2 également) toute la force de cisaillement est contrée par la résistance à la rupture des racines, et non par la résistance au glissement. On ne tient pas compte de la friction sol-racine.	La force de friction sol-racine doit également être prise en compte, car beaucoup de racines glissent avant même de casser (Schmidt et al. 2001). Waldron et Dakessian (1981), Ennos (1991), Pollen (2007), ont développé une fonction pour quantifier les forces de friction basée sur la longueur de la racine et la force du lien sol-racine. Ces travaux font intervenir une longueur et un diamètre racinaires critiques au-delà desquels les racines cassent.
Architecture	(5) initialement à la tension, toutes les racines sont orientées perpendiculairement à la surface de cisaillement. Ceci permet des simplifications sur les forces normales au plan de cisaillement. Des travaux montrent que les résultats sont identiques que l'on applique cette hypothèse ou que les racines soient distribuées au hasard (Gray & Ohashi 1983)	De plus en plus de travaux (Mickovski & van Beek 2008) avancent que le fait de considérer que toutes les racines sont initialement perpendiculaires au plan de cisaillement participe à la surestimation de la cohésion additionnelle, et préconisent davantage de recherches sur l'angle des racines par rapport au plan de cisaillement.
Architecture	(6) l'angle de cisaillement de la racine (α dans le modèle W&W's) est compris entre 40° et 70° par rapport à la perpendiculaire de la surface de	La fourchette 40 à 70° doit être précisée en fonction des espèces et du sol car les conséquences ne sont pas négligeables sur le facteur de 1.2

	glissement et cet angle de cisaillement ne dépend pas de l'humidité du sol	proposé par W&W's (Thomas & Pollen-Bankhead 2010).
Biomécanique et architecture	(7) l'angle de frottement interne du sol Φ est compris entre 25° et 60°, l'angle de frottement interne Φ ne dépend pas de la présence des racines (Operstein & Frydman 2000, O'Loughlin & Ziemer 1982, Waldron & Dakessian 1981, Gray & Megahan 1981, Waldron 1977, O'Loughlin 1974)	La fourchette 25 à 60° semble correcte pour Φ, mais très large (Wu et al. 1988). Elle doit être affinée en fonction du type de sol, elle a également un impact sur le facteur 1,2. Par ailleurs, des travaux en laboratoire montrent que les racines pourraient avoir un impact sur Φ (Graf et al. 2009, Endo & Tsuruta 1969).
Architecture	(10) la somme des résistances à la tension de chaque racine est égale à la somme des racines multipliée par une résistance à la tension moyenne, et ce quelle que soit la quantité de racines dans le sol, c'est-à-dire quelle que soit la valeur du RAR	Des travaux (Shewbridge & Sitar 1989) ont montré que la cohésion additionnelle apportée par les racines augmente de façon sensiblement non linéaire quand il y a beaucoup de racines dans le sol. Si RAR > 0,005, il faut se méfier : il est probable que la cohésion additionnelle soit surestimée.
=> Nécessité d'intégrer également l'hydrologie	(11) on ne tient pas compte de l'effet de la pression hydrostatique du sol sur la cohésion additionnelle (ni a fortiori sur les points abordés ci-dessus comme les propriétés mécaniques des racines, la force du lien sol-racines, l'angle de cisaillement de la racine, l'angle de frottement interne du sol…)	

II. QUESTIONNEMENT SCIENTIFIQUE, STRUCTURE DE LA THÈSE

II. 1. Objectif de la thèse et questions afférentes

Il a été montré ci-dessus que les glissements de terrain superficiels figurent parmi les risques naturels les plus importants en Chine du Sud, d'autant qu'ils sont augmentés par la recrudescence d'initiatives de développement humaines, mais qu'ils peuvent être efficacement évités même en régions reculées par des actions d'éco-ingénierie utilisant la végétation sur des zones restreintes bien localisées. Le choix de la végétation utilisée doit être judicieux à la fois d'un point de vue technique et économique et doit se faire au regard des conditions locales. Il existe donc un réel besoin d'investigation dans ce domaine.

Dans le périmètre des cadres présentés ci-dessus, cette thèse a pour objectif de répondre à la question :
Quelles sont les propriétés racinaires dont dépend le plus la stabilisation de la pente (objectif scientifique) ?
Puis cette réflexion sera appliquée aux espèces végétales présentes sur les pentes de Chine du Sud afin d'identifier celles qui seraient les meilleures « espèces-outils » (objectif pratique).

Cet objectif soulève d'autres questions. Parmi les propriétés racinaires, est-il suffisant de ne s'intéresser qu'aux propriétés mécaniques et architecturales ou faut-il prendre en compte d'autres propriétés racinaires ? Est-ce que la présence de plantes sur une pente instable a toujours un effet bénéfique, stabilisateur de la pente ? Un effet *a priori* bénéfique ne peut-il pas s'avérer négatif, en particulier quand le changement d'échelle fait intervenir d'autres mécanismes dans la stabilité d'une pente ?

II. 2. Présentation de la démarche scientifique

I. 2. a. Définitions et postulats préalables

Afin de répondre à l'objectif de la thèse, il est nécessaire de définir quelques notions méthodologiques et postulats.

Définition de « trait » :
Les comparaisons entre individus et/ou espèces nécessitent de pouvoir quantifier des propriétés. On fera donc appel à la notion de trait. Un trait est une propriété bien définie et mesurable d'un organisme, généralement mesurée à l'échelle de l'individu et utilisée à des fins de comparaison entre les espèces. Un trait est dit fonctionnel quand il influence fortement la performance de l'organisme dans son environnement, en l'occurrence ici la performance d'une plante à retenir la pente (McGill et al. 2006).

Postulat n°1 :
Comme présenté dans cette introduction, les traits architecturaux et biomécaniques présentent un grand intérêt dans l'étude de la stabilité des pentes. Même si, au cours de cette thèse, est étudié un large panel de traits racinaires et aériens, il est décidé de mettre l'accent sur l'architecture racinaire, qui

présente une complexité qu'il convient d'approfondir. L'étude de l'architecture du système racinaire permet d'intégrer les traits racinaires à l'échelle du système racinaire, donc de la plante et de l'espèce. En effet, le contexte sociologique dans lequel se place cette thèse amène à se poser la question des meilleures « plantes –outils » pour la stabilisation des pentes, et l'étude comparée des traits à l'échelle de l'espèce se justifie.

Postulat n°2 :
En ce qui concerne l'étude de l'architecture racinaire, la démarche « espèce » peut être simplifiée par une démarche « type racinaire ». Cette thèse en éco-ingénierie a but pour de préconiser des espèces-outils efficaces pour la stabilisation des pentes ; les espèces sont facilement identifiables sur le terrain. Cependant, lorsqu'il s'agit de mieux comprendre les effets de l'architecture racinaire, il est possible de raisonner non plus en termes d'espèce mais en termes de type racinaire. Un type racinaire est représenté par une gamme de traits racinaires. Un type racinaire est donc plus générique qu'une espèce. Si besoin, on peut ensuite remonter aux espèces à différents stades ontologiques par le biais de ces traits racinaires.

Définition de « hotspot » :
Les points chauds de dégradation des milieux (ou « degradation hotspots ») sont définis comme les zones sources de sédiments (Baigorria & Romero 2007). Ce sont aussi les zones où la dégradation des sols se situe bien au-dessus des seuils de tolérance, c'est-à-dire au-dessus d'une capacité de reconstitution naturelle. Par exemple les zones de forte pente où le sol est à nu, ou encore les rigoles où se concentrent les ruissellements (Poesen et al. 2008). Ils sont également définis comme les endroits qui, quand ils ne sont pas correctement pris en compte, peuvent être la source d'une dégradation à grande échelle. Un autre exemple est les terrasses qui présentent une contre-pente à l'extrémité de leur surface subhorizontale, près du muret. Cette contre-pente agit comme un collecteur des écoulements de toute la zone. Si ce point chaud n'est pas correctement corrigé, l'eau pourra déborder (voire s'écouler en endommageant le muret) en emportant une grande quantité de dépôts, augmentant ainsi la nocivité de l'écoulement (Hooke et al. 2007). Toujours dans le contexte sociologique et politique de cette thèse, il est pertinent de se poser la question des meilleures associations d'espèces à l'échelle des points chauds de dégradation. En effet, dans des conditions où les moyens sont restreints, où la main d'œuvre locale est facilement mobilisable dans l'urgence mais pas forcément à grande échelle sur le long terme et où le foncier est très demandé en particulier pour un usage agricole, des actions de stabilisation rapides sur des zones bien ciblées auront davantage de résultats que des actions lourdes sur des surfaces dégradées importantes (*Figure 3*). Dans cette optique, les plantes étudiées seront préférentiellement des individus jeunes puisqu'il s'agit d'identifier les espèces-outils efficaces pour la stabilisation des pentes dès leurs premiers stades de développement.

Figure 3 : Points chauds de dégradation
a) Porter les actions de restauration rapidement et précisément sur les points chauds de dégradation (ovales) pourrait éviter la dégradation de zones plus étendues et l'export d'importants volumes de sol, photo : M. Ghestem, route Kunming-Liuku 2009; b) Cette pente a été détruite par un glissement de terrain dans les années 1970. Cette zone était presque stabilisée par des rangs d'*Agava americana* plantés il y a une dizaine d'années (accolades), mais la construction d'une piste en 2005 traversant des zones sensibles en amont a pour conséquence la création de rigoles dangereuses qui dégradent à nouveau cette pente, photo : A. Stokes, vallée de la Salween, 2009.

Initialement, ce projet de thèse était construit pour ne s'intéresser qu'aux apports mécaniques des racines, *a priori* positifs sur la stabilité des pentes. Il était prévu de partir de l'étude des traits mécaniques et architecturaux des racines jusqu'à l'intégration au niveau de la pente à l'aide de simulations numériques. Toutefois, au fil des observations sur le terrain, des collaborations construites pendant ces trois années et des résultats d'expériences, sont apparus des effets mitigés voire négatifs des racines sur la résistance au cisaillement des sols. Ces effets étaient le fait de mécanismes hydriques comme expliqué ci-dessus, mais également mécaniques. Il a semblé intéressant d'élargir le cadre de la thèse. Par ailleurs, on a eu l'opportunité d'étudier également d'autres traits racinaires que les seuls traits mécaniques et architecturaux, tels que les traits chimiques, physiologiques et structuraux qui sont liés à la survie des racines ainsi qu'à leur capacité d'absorption et de conservation des ressources. La prise en compte de ces traits est importante pour évaluer la persistance des racines dans un milieu. L'élargissement du cadre scientifique de l'étude a nécessité un resserrement des domaines scientifiques abordés. La numérisation et la modélisation (mathématiques appliquées) ont donc été abordées de façon moins aboutie qu'initialement prévu. Elles apparaissent toutefois dans des travaux parallèles et dans des travaux préliminaires qui alimentent les perspectives de recherches ultérieures.

La démarche scientifique suivante a été suivie :

- Dans un premier temps : sur le terrain en Chine, où il est compliqué de mettre en œuvre des mesures de stabilité des pentes, on s'est contenté de mesurer les traits végétaux. Par le temps et les efforts non investis dans les mesures de stabilité des pentes, on a pu élargir la gamme d'espèces mesurées et la gamme des traits considérés, en ne prenant pas uniquement en compte des traits racinaires architecturaux et biomécaniques, mais en considérant également des traits représentatifs de l'écologie des racines en particulier et des plantes en général.

- Ensuite, comme on souhaitait mettre l'accent sur les effets des traits racinaires architecturaux, les mesures de traits et des réponses ont été mises en place en laboratoire, en France, non plus sur une large gamme d'espèces mais sur une gamme restreinte de types racinaires bien distincts les uns des autres.

La démarche suivie présente une limite majeure :
On propose une sélection d'espèces chinoises « efficaces » en s'appuyant sur des conclusions de la littérature pour la définition de l' « efficacité » d'une espèce. Il n'y a pas eu de « retour » entre les mesures en laboratoire et la redéfinition de l'efficacité d'une espèce. En effet, les mesures de laboratoire permettent de conclure sur l'efficacité avérée de tel ou tel type racinaire et l'importance de l'influence de tel ou tel trait architectural particulier. Il aurait été intéressant de s'appuyer sur ces mesures traits/effet pour vérifier *a posteriori* l'efficacité des espèces chinoises étudiées. Seuls les traits d'architecture racinaire ont été mesurés à la fois sur leurs effets (= leur efficacité) sur la stabilité de la pente, mais également sur la réponse de la pente (= la variation de la stabilité de la pente en fonction de la variation des traits architecturaux). Cependant, les mesures de terrain ayant eu lieu avant les mesures en laboratoire, les traits architecturaux mesurés sur le terrain ne sont pas identiques à ceux mesurés en laboratoire, ils sont souvent moins précis et moins exploitables.

I. 2. b. Présentation du plan de la thèse

La thèse présente d'abord les résultats scientifiques fondamentaux concernant les effets de l'architecture racinaire sur la stabilité des pentes. Elle se poursuit par la prise en compte d'autres traits racinaires afin d'appliquer cette réflexion au terrain de la Chine du Sud. Elle est donc composée de deux chapitres de deux parties chacun (*Figure 4*).

Chapitre I : Par quels processus l'architecture racinaire influence-t-elle la stabilité des pentes ?
Ce chapitre présente deux démarches parallèles et complémentaires. La première s'intéresse aux processus mécaniques, qui sont mesurés par des tests en laboratoires (première partie). La seconde s'intéresse aux processus hydriques et résulte d'une réflexion sur la base d'une revue bibliographique (deuxième partie)
Questions abordées :

Partie 1 : Quel est le meilleur type d'architecture racinaire et les traits racinaires architecturaux les plus importants pour la résistance mécanique au cisaillement ?

Partie 2 : Quel sont les effets de l'architecture racinaire sur les processus hydriques dans les pentes ?

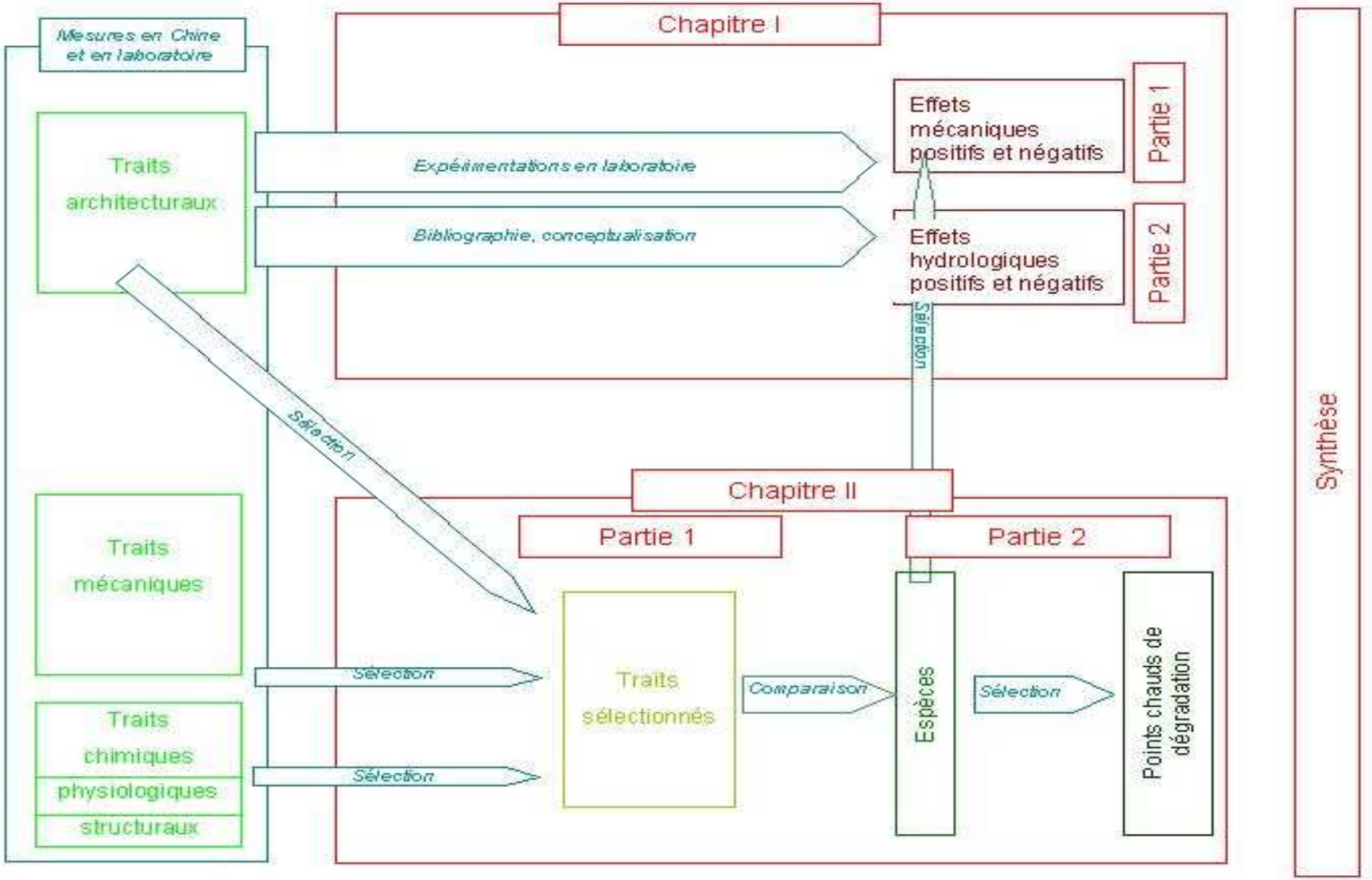
Chapitre II : Quelles sont les espèces-outils les plus efficaces pour la stabilisation des points chauds de dégradation en Chine du Sud ?
Ce chapitre suit une démarche par étapes successives qui permet tout d'abord d'identifier un panel de traits pertinent et non redondant pour évaluer l'efficacité d'une espèce (première partie) et ensuite de s'appuyer sur ce panel plus quelques traits distincts pour sélectionner les espèces les plus efficaces.
Les questions abordées sont donc :

Partie 1 : Sélection des traits racinaires biomécaniques et écologiques les plus représentatifs. Est-ce que les traits biomécaniques sont représentatifs des traits écologiques des racines, sont-il redondants ?

Partie 2 : Par l'étude des traits sélectionnés, quelles sont les espèces et les associations d'espèces les plus efficaces pour stabiliser les fortes pentes ?

La discussion finale présente une synthèse des chapitres I et II afin de répondre au questionnement initial, détaille les limites de l'étude, avance des réponses aux questionnements subsistant et le cas échéant propose des pistes de recherche pour l'avenir.

Figure 4 : Diagramme de la structure de la thèse



III. PRÉSENTATION DES SITES D'ÉTUDE

III. 1. Le terrain en Chine du Sud

III. 1. a. Localisation géographique et administrative

Le site d'étude est localisé à l'extrême ouest de la province chinoise du Yunnan, à la frontière birmane (*Figure 5a*), plus précisément dans le village de Daxindi, sur les rives de la Salween (Nujiang en chinois).

Figure 5 : Localisation du site chinois
a) Situation géographique de la zone d'étude : à l'extrême ouest de la province du Yunnan, à la frontière avec la Birmanie ; b) Le bassin versant de la Salween traverse des milieux très divers et s'étend sur plusieurs pays, source : http://earthtrends.wri.org/text/water-resources/map-369.html

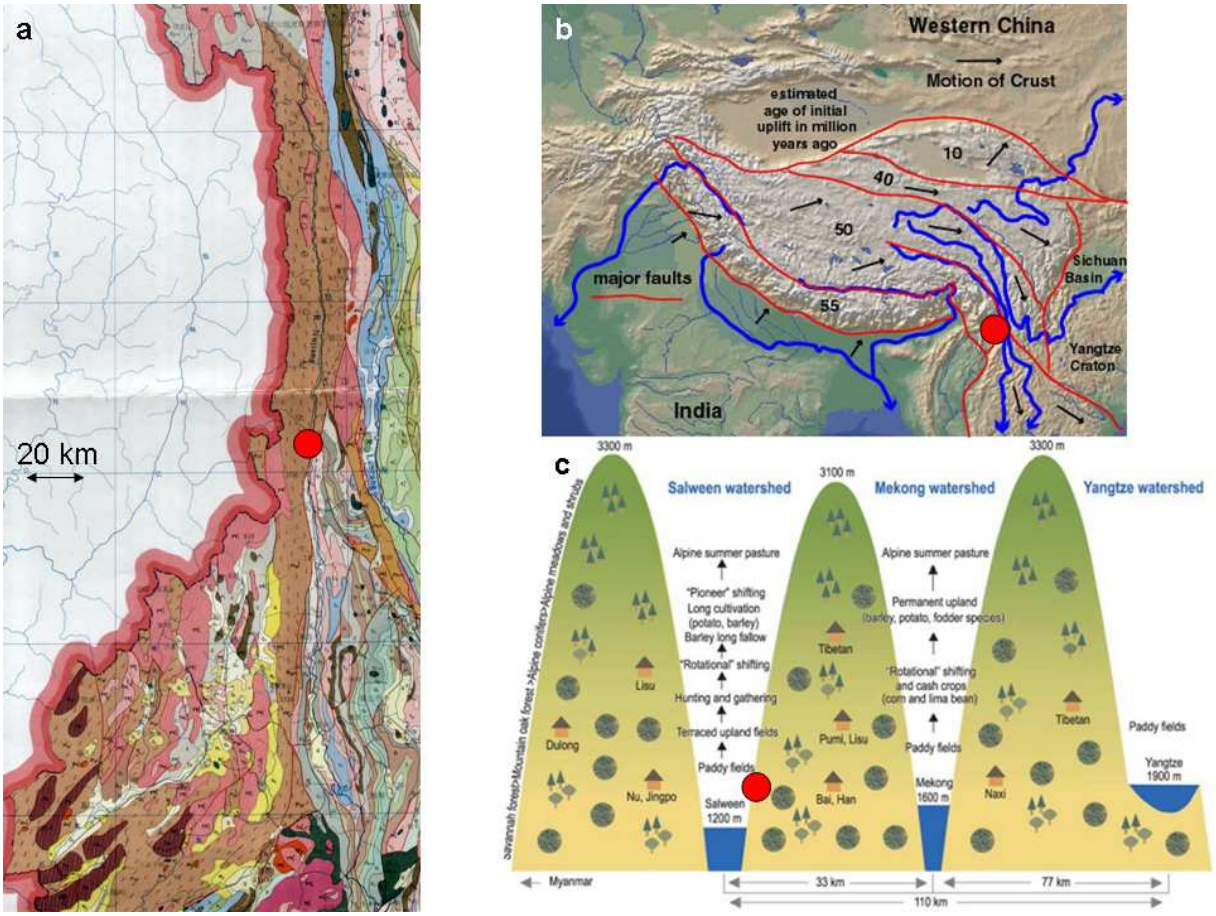
La Salween prend sa source sur le plateau tibétain, traverse le sud-ouest de la Chine, la Birmanie, frôle la Thaïlande, avant de se jeter dans la mer d'Adaman, en Birmanie (*Figure 5b*). C'est le deuxième plus grand fleuve de l'Asie du Sud-Est après le Mékong. La densité de population dans ce bassin est de 76 hab/km². Il aurait perdu 72% de sa forêt originelle, et présente un taux annuel de déforestation de 10% (communication « Earth Trends 2002 » du World Resources Institute). La Salween n'est pas encore équipée hydro électriquement, mais un grand projet émanant du gouvernement provincial du Yunnan à Kunming prévoit la construction de 13 barrages sur sa partie chinoise (International River Network, www.irn.org).

Dans la la préfecture autonome lisu de Nujiang, la minorité ethnique principale sont les Lisus : ils représentent 39% de la population de cette préfecture et 40% des Lisus du Yunnan. Dans le Yunnan, les Lisus étaient 578 000 en 1995 (Ji et al. 2005) et 557 150 en 1999. Ils sont environ 1 million dans le monde entier : 60% vivent en Chine (dont 98% dans le Yunnan), et les 40% restants sont éparpillés dans 18 pays sud-asiatiques, européens et américains. Ils sont majoritairement de religion catholique. La préfecture autonome lisu de Nujiang est actuellement la plus pauvre préfecture du Yunnan (Editorial Commitee of Yunnan Statistics Yearbook 2000) ; le revenu moyen y est de 250 €/an. 94% de la population vit en zone rurale, et le taux d'analphabétisation est assez élevé, il atteint 70% chez les femmes. Comme plus de 80% de la population mondiale (OMS, UICN et WWF, 1993), les populations rurales utilisent les plantes médicinales pour leur santé et pour le commerce. 80% de ces plantes sont sauvages, 12% sont semi-cultivées et 8% complètement domestiquées. 21% sont menacées d'extinction, à cause de la déforestation et de leur collecte pour la commercialisation (25% sont largement commercialisées, (Ji et al. 2005).

III. 1. b. Une géologie complexe engendrant une biodiversité remarquable

L'histoire géologique du site d'étude remonte principalement aux derniers 50 Ma, qui ont vu la collision entre la plaque indienne et la plaque eurasienne, la fermeture de l'ancienne Téthys et le soulèvement de la chaîne de l'Himalaya et le plateau tibétain. Les altitudes sont donc abruptes : de 800 m sur les rives de la Salween à plus de 3 000 m sur les plus hauts sommets avoisinants. Les nombreuses failles tectoniques témoignent de ces mouvements profonds qui ont fait affleurer des couches géologiques diverses : Protérozoïque (-2 000 Ma) jouxtant du Dévonien, Carbonifère et Triassique (-300 Ma). Une faille se situe juste dans le cours de la Salween, et donc la géologie est complètement différente d'un versant de la Salween à l'autre (*Figure 6a et b*). Il en résulte des caractéristiques pédologiques également très diverses.
Le climat profite de l'influence à la fois de la montagne et de la mousson. Il est tempéré sur toute l'année. La température moyenne maximale annuelle ne dépasse pas 21,5 °C. Les températures moyennes minimales dans les mois les plus frais (hiver : novembre à avril) sont autour de 6 °C. Il ne gèle pas souvent. La pluviométrie annuelle est de 1 100 mm, dont 60 % tombent entre juin et août.

Figure 6 : Géologie et topographie du site chinois
a) Carte géologique de la zone d'étude : juxtaposition de nombreux substrats géologiques différents (le point rouge est le village de Daxindi) ; b) Les grands fleuves descendant du plateau tibétain et failles tectoniques majeures de la région, source : P. Winn, www.shangri-la-river-expeditions.com ; c) Schéma des trois vallées parallèles (ce schéma n'est pas à l'échelle, (Weyerhaeuser & Kahrl 2006).



Le Fleuve Salween est l'un des trois grands fleuves qui coulent parallèlement l'un à côté de l'autre depuis leur source sur le plateau tibétain : le Fleuve Bleu, le Mékong et la Salween (Figure 6b et c). La

Région des Trois Fleuves a été classée au Patrimoine mondial de l'UNESCO en 2003. Le nord-ouest du Yunnan est la région de Chine présentant la plus riche biodiversité et c'est peut-être la région tempérée la plus diverse de la terre sur le plan biologique (Unesco, http://whc.unesco.org/fr/list/1083). La diversité topographique et climatique extraordinaire du site, associée à son emplacement à la jonction des domaines biogéographiques d'Asie de l'Est, d'Asie du Sud-est et du Plateau tibétain et sa fonction de corridor nord-sud pour le déplacement des plantes et des animaux (en particulier durant les âges glaciaires) en fait un paysage réellement unique. Ce site des Trois Fleuves comprend 6 000 espèces végétales différentes et plus de 25% des espèces animales du globe, soit 50% des espèces animales de Chine. C'est l'habitat menacé du tigre, du léopard, de l'ours, des cervidés et des rapaces. Plus de 300 plantes médicinales y sont présentes. Il est intéressant de noter que la zone inscrite au patrimoine de l'UNESCO est en fait composée de 8 parties non contiguës couvrant les sommets au-dessus des cours des fleuves. Une description plus détaillée du site précis sur lequel ont eu lieu les prélèvements est présentée dans le Chapitre I, partie 2.

III. 2. Les laboratoires

III. 2. a. UMR Amap, Montpellier

L'Umr Amap n'est *a priori* pas un laboratoire d'expérimentation mais de numérisation. Les chercheurs de cette unité mixte de recherche mènent leurs recherches de terrain à différents endroits du globe. Cependant, pour les besoins de cette thèse, le laboratoire s'est doté de différents équipements :

- une machine de cisaillement direct pour mesurer les caractéristiques de cisaillement (cohésion, angle de frottement, forme de la courbe de déformation) de petits échantillons de sol (6*6*2 cm^3, *Figure 7a*) selon la norme NF P94-070 (Afnor 1996) ;
- un dispositif de cisaillement de plus grandes dimensions conçu par l'atelier du Cirad pour répondre aux besoins de cette thèse (*Figure 7b*). Ce dispositif est composé d'un boitier inférieur (50*70*15 cm^3) se déplaçant sur un boitier inférieur (50*50*15 cm^3). Afin d'éviter tout frottement horizontal et latéral entre les deux boitiers lors du déplacement, un espace de quelques mm existe entre les deux boitiers grâce à des roulettes horizontales et verticales guidées par des rails fixés aux parois latérales extérieures du boitier inférieur. Le boîtier inférieur est plus long que le boîtier supérieur afin de limiter les effets de bord parfois observés sur le plan de cisaillement au niveau du chevauchement des parois antérieures des boitiers. Cela permet également de raisonner à surface de cisaillement constante. Le boîtier supérieur est tiré par un treuil électrique de vitesse constante modulable. Le treuil est relié au boitier par des tiges de métal pour éviter toute élongation lors du test. Entre le treuil et le boitier est fixé un capteur de force en fonction du temps, qui nous permet de tracer la courbe contrainte : déformation à vitesse connue. Le boitier inférieur est enchâssé dans un coffrage métallique en butée sur le point d'attache du treuil grâce à une tige en métal de section carrée indéformable. Les boitiers sont constitué de PVC 7 mm d'épaisseur, renforcés par des tiges métalliques latérales et des coins métalliques afin d'éviter toute déformation pendant le test.

Figure 7 : Dispositifs expérimentaux
a) Machine de cisaillement direct en laboratoire ; b) Dispositif de cisaillement à Montpellier ; c) Plants en boîtes de cisaillement à la pépinière de Aix-les Milles ; d) Machine de cisaillement Casagrande au Cemagref de Aix-le Tholonnet.

III. 2. b. Cemagref du Tholonnet et pépinière de Aix-les Milles

Afin de procéder à des expérimentations dans des conditions plus pointues (mesures de force et de déplacement encore plus précises et reproductibles, dispositif encore moins déformable), ont été effectués des tests de cisaillement dans la boite de Casagrande du laboratoire de mécanique des sols du Cémagref du Tholonnet (Aix-en-Provence, *Figure 7d*). Cette boite de Casagrande est composée de deux boitiers de 50*50*15 cm^3 chacun, disposés dans un châssis extrêmement rigide puisque cette machine sert normalement au test de matériaux de construction (bétons…) Nous avons pu profiter pour ces tests de l'expertise des techniciens et ingénieurs du laboratoire.
Les tests effectués au Tholonnet consistaient au cisaillement de sol traversé par des racines réelles de plantes qui avaient poussé dans des boitiers PVC spécialement conçus pour les besoins de l'expérience (boitiers en deux parties de 49*49*14 cm^3 chacune). Les plantes avaient été hébergées et soignées à la pépinière départementale d'Etat de Aix-en-Provence-les Milles à partir du stade jeune plant pendant 10 mois (*Figure 7c*).

CHAPITRE I

PAR QUELS PROCESSUS L'ARCHITECTURE RACINAIRE INFLUENCE-T-ELLE LA STABILITÉ DES PENTES ?

INTRODUCTION AU PREMIER CHAPITRE

Ce chapitre a pour objectif de compléter les connaissances sur les effets des traits architecturaux sur la stabilité des pentes et d'analyser leurs effets croisés de façon précise. Comme indiqué dans l'introduction générale à ce travail, les traits racinaires pris en compte pour calculer la cohésion additionnelle apportée par les racines dans une pente sont principalement un trait biomécanique : la résistance maximale des racines à la traction, multiplié par un trait architectural : la surface cumulée des sections des racines qui traversent le plan potentiel de cisaillement. Grâce à ces deux traits, il existe un modèle simple qui permet de calculer la cohésion additionnelle apportée par les racines. Néanmoins, l'architecture des systèmes racinaires peut jouer un rôle plus complexe que celui de simple multiplicateur de traits racinaires individuels. L'architecture racinaire n'est pas uniquement une juxtaposition de traits racinaires individuels car cette juxtaposition peut entraîner des combinaisons de traits qui, à l'échelle du système racinaire, ont des effets différents de leur simple somme. C'est ce que le premier chapitre s'efforce de mettre en évidence, par une étude approfondie des effets de l'architecture racinaire.

La première partie se focalise sur les effets de l'architecture racinaire sur la résistance au cisaillement. Afin de mesurer ces effets, des tests de cisaillement sont effectués en laboratoire, ce qui permet des conditions reproductibles avec des paramètres finement contrôlables. Trois espèces aux systèmes racinaires bien distincts ont été testées. Ces espèces ont été choisies selon différents critères qui ne sont pas détaillés dans cette première partie elle-même, le format d'article ne permettant pas les explications trop longues. La démarche de sélection des espèces est donc reprise dans l'*encadré v*.
La seconde partie se concentre sur les effets de l'architecture racinaire sur l'hydrologie des pentes, qui influence elle aussi la résistance au cisaillement. Parce que ces effets ne sont réellement étudiés que depuis peu, cette seconde partie ne présente pas de données acquises durant la thèse mais est principalement le fruit de réflexions et de conceptualisation.

Encadré v : Choix des espèces testées dans la partie 1 du premier chapitre

To choose species to test among the large biodiversity found on Yunnan slopes, seeds of 18 species found on these slopes were gathered. Because they are not well-known species, care had to be taken on sowing conditions. Dormancy breakage and growing protocols were documented in particular with the help of Kew Botanical Garden. For each species, several seed samples were germinated with/without previous dormancy breakage and with/without previous treatment with growing enzyme (gibberellins). Dormancy breakage took place in winter 2009-2010. In spring 2010, seeds were sown in wet soil mold (to facilitate initial growth) directly surrounded by some soil used to fill in the shear boxes (so growing roots were rapidly immerged in their later environment). Germination success rates after 2 months (May 2010) are presented in Table v-1. Among species with rather high germination success rates, we chose those with more than 9 individuals to be tested, we opted for species of the same functional group (grass/annual or biannual shrub/liana/tree) to reduce factors of variation with a preference for perennial plants which can be used in the long term in eco-engineering actions, and we searched for species known a priori to present different root system types. We ended with 3 tree species used in reforestation programs in Southern China: *Jatropha curcas* L., *Rhus chinensis* L. and *Ricinus communis* Miller.

Table v-1: Germination success rates for tested species.
a: annual, ba: bisannual, h: herb, l: liana, t: tree. ND: non dormant, PC: physical dormancy (seeds with physical dormancy have hard seed coats that do not allow the seed to absorb water. Dormancy breakage simply consists in cutting a very small hole in the fruit or seed coat), PL: physiological dormancy (biochemical inhibitors. To counteract them, seeds have to stay in wet and cold conditions during at least 2 months. After the cold stratification treatment, seeds are moved to room temperatures). N: treatment (dormancy breakage or enzyme) not applied, Y: treatment applied. * species attacked by *Deroceras reticulatum* slugs.

Species	Functional group	Dormancy	Gibberrelline	Germination success rate (%)
Amaranthus cruentus	a	ND	N	33
		ND	Y	29
Amaranthus hypocondriacus	a	ND	N	10
		ND	Y	15
Artemisia annua	ba	ND	N	2
		ND	Y	ε
Artemisia lavandulaefolia	ba	ND	N	ε
		ND	Y	0
Bauhinia championii	l	PC	N	0
Broussonetia papyrifera	t	N	Y	0
		PC	Y	0
*Chloris truncata**	h	ND	N	ε
		ND	Y	0
Cotoneaster hebephyllus	t	N	N	0
		N	Y	0
		PL	N	0
Fagopyrum esculentum	a	ND	N	73
		ND	Y	77
Jatropha curcas	t	N	N	33
		N	Y	57
		PL	N	15
		PL	Y	0
Phyllanthus emblica	t	ND	N	0
Pistacia chinensis	t	PL	N	0
		PL	Y	3
Pueraria lobota	l	N	N	20
		N	Y	30
		PL	N	0
		PL	Y	10
Pueraria stricta	t	PS	N	5
		PS	Y	10
Pyracantha fortunea	t	N	N	0
		N	Y	0
		PL	N	0
		PL	Y	0
*Rhus chinensis**	t	PL	N	3
		PL	Y	2
Ricinus communis	t	N	N	60
		N	Y	38
		PL	N	0
		PL	Y	54
Vernicia fordii	t	ND	N	0
		ND	Y	0

I. 1. INFLUENCE DE L'ARCHITECTURE RACINAIRE SUR LA RÉSISTANCE MÉCANIQUE

► Ghestem, Veylon, Bernard, Vanel, Stokes. Influence of root system morphology and architectural traits on soil shear resistance. Prêt pour Plant and Soil.

Background and Aims: Vegetation can be used to stabilise slopes with regard to shallow landslides, but the optimal plant architecture for conferring resistance is not known. This study aims at identifying root morphological traits which confer the most resistance to soil during shearing.
Methods: Three species (*Ricinus communis* L., *Jatropha curcas* L. and *Rhus chinensis* Mill.) were grown in large shear boxes for 10 months. Direct shear box tests were then performed on the rooted soil and compared to fallow soil. Root systems were excavated and a large number of traits measured.
Results: Shear strength and deformation energy were enhanced by the presence of roots. Regardless of confining pressure, *R. communis* conferred most resistance to shear due to its taprooted system with many vertical roots. *J. curcas* possessed oblique and vertical roots which might have created fragile zones through soil profile. The least efficient root system with regard to resisting shear, was R. chinensis which possessed many horizontal lateral roots. Soil mechanical properties were most influenced by (i) density of roots crossing the shear plane, (ii) branching density throughout soil depth, (iii) total length of coarse roots above the shear plane and (iv) total volume of coarse roots and fine root density below the shear plane. During failure, fine, short and branched roots slipped through soil rather than breaking.
Conclusion: Root morphological traits such as root density, branching, length, volume inclination and orientation can influence significantly soil mechanical properties.

I. 2. INFLUENCE DE L'ARCHITECTURE RACINAIRE SUR LES FLUX HYDRIQUES

► Ghestem, Sidle, Stokes. 2011. The influence of plant root systems on subsurface flow: Implications for slope stability. BioScience 61: 869-879. doi: 10.1525/bio.2011.61.11.6.

Although research has explained how plant roots mechanically stabilize soils, in this article we explore how root systems create networks of preferential flow and thus influence water pressures in soils to trigger landslides. Root systems may alter subsurface flow: Hydrological mechanisms that promote lower pore-water pressures in soils are beneficial to slope stability, whereas those increasing pore pressure are adverse. Preferential flow of water occurs in the following types of root channels: (a) channels formed by dead or decaying roots, (b) channels formed by decayed roots that are newly occupied by living roots, and (c) channels formed around live roots. The architectural analysis of root systems improves our understanding of how roots grow initially, develop, die, and interconnect. Conceptual examples and case studies are presented to illustrate how root architecture and diverse traits (e.g., diameter, length, orientation, topology, sinuosity, decay rate) affect the creation of root channels and thus affect preferential flow.

SYNTHESE DU PREMIER CHAPITRE

Dans les deux parties de ce chapitre, de nombreux traits et types architecturaux racinaires sont présentés et analysés au regard de leur réponse au cisaillement, tant par les processus purement

mécaniques que par les processus où l'hydrologie est en jeu. De nombreux effets positifs ont été mis en évidence, qui montrent que certains traits et types architecturaux bien identifiés augmentent la résistance au cisaillement d'une pente. *A contrario*, des effets non significatifs voire négatifs des racines sur la résistance au cisaillement de la pente ont été mis en évidence.
La première partie montre tout d'abord que la présence de racines agit positivement sur la résistance maximale au cisaillement et sur l'énergie nécessaire pour déformer un sol jusqu'à sa rupture, et dans une moindre mesure sur la déformation latérale qu'il subit avant la rupture. Par contre la présence de racines n'agit pas sur l'élasticité d'un sol. La résistance résiduelle après la rupture dépend davantage de la pression de confinement et de l'humidité du sol que de la présence de racines. Ensuite, cette étude montre que le type de système racinaire qui augmente le plus la résistance au cisaillement est celui composé d'un large collet qui se divise rapidement en plusieurs racines plongeantes portant de nombreuses racines fines (*Ricinus communis*). Ce type de système racinaire est proche du type « traçant » même s'il n'y a pas une unique racine plongeante, mais plutôt un faisceau de racines plongeantes épaisses qui jouent le rôle de levier lors du cisaillement. Les racines fines quant à elles jouent le rôle d'ancrage local tout le long des racines épaisses. En effet, un système racinaire également composé de racines épaisses mais avec une ramification moins dense (*Jatropha curcas*) aura une efficacité moindre dans la résistance au cisaillement. Il est possible que des racines épaisses inclinées principalement de 30 à 60° et sans ramifications jouent le rôle de lignes de fragilité. Des systèmes racinaires composés de nombreuses racines fines sans racines épaisses robustes pour les relier solidement à une structure cohérente (*Rhus chinensis*) semblent peu efficaces pour retenir un glissement de terrain. Il est possible que de très nombreuses racines fines désagrègent le sol, surtout lorsqu'elles sont concentrées en des zones très localisées qui deviennent alors des zones de fragilité. A l'aune de cette première partie, on perçoit que les fragilités mécaniques peuvent se cumuler avec des phénomènes hydriques eux aussi fragilisants. En effet, la deuxième partie explique que tout trait architectural ou tout type d'architecture racinaire qui augmente localement la pression interstitielle du sol crée une zone de fragilité à partir de laquelle peuvent se déclencher des glissements de terrain. En particulier, le long de racines lisses sans ancrage régulier par des ramifications, l'eau peut s'infiltrer facilement et diminuer davantage les liens entre les racines et le sol environnant. D'autre part, lorsque les racines fines, très nombreuses et denses, forment des structures ressemblant à des éponges, l'eau peut également s'accumuler et fragiliser la zone. Il est donc nécessaire, pour toute étude ultérieure sur les effets des plantes sur le déclenchement des glissements de terrain, de considérer simultanément les deux types de processus en jeu – mécaniques et hydriques – en connaissant l'organisation spatiale des racines dans le sol. L'architecture racinaire est une approche intéressante car elle permet de se placer à l'interface entre ces deux domaines – la mécanique des sols et des racines et l'hydrologie des pentes – et d'en tirer des conclusions sur les risques potentiels de glissement de terrain.

Ce premier chapitre permet donc de répondre à la question posée : les processus par lesquels l'architecture racinaire influence la stabilité des pentes sont synthétisés dans le *tableau 3*. Ils se résument ainsi : du point de vue mécanique comme du point de vue hydrique, c'est la conjonction des effets des racines de structure et des racines fines qui importe.
Les racines de structure sans racines fines ne sont pas optimales et peuvent même faire apparaître des lignes de fragilité. Plus précisément, les racines de structure sont particulièrement bienvenues dans les secteurs perpendiculaires à la pente vers l'aval de la pente pour des raisons à la fois mécaniques et hydriques.
Les racines fines sans racines de structure ne sont pas optimales non plus, elles peuvent faire apparaître localement des zones de faiblesse qui, si elles sont proches, peuvent participer au déclenchement d'un glissement de terrain.
L'organisation des ramifications est particulièrement importante : denses sur tout le profil racinaire, elles améliorent la stabilité mécanique. Orientées vers l'aval de la pente, elles améliorent la stabilité hydrique.

Tableau 3 : Synthèse des effets mécaniques et hydriques des traits et systèmes racinaires

	Processus mécaniques	Processus hydriques
Traits racinaires bénéfiques	Au-dessus du plan de cisaillement : - longueur totale des racines de structure, en particulier en aval de la tige - densité de ramification Au plan de cisaillement : - nombre de racines de structure, en particulier sub-verticales en aval de la tige - masse de racines fines En-dessous du plan de cisaillement : - volume de racines de structure, en particulier perpendiculaires au sens de cisaillement - masse de racines fines - densité de ramification	- longues racines orientées vers l'aval de la pente - concentration d'extrémités racinaires orientées vers l'aval de la pente - ramifications orientées vers le bas de la pente - sinuosités orientées vers le haut de la pente
Types racinaires bénéfiques	Type « multi-pivotant », composé d'un large collet qui se divise rapidement en plusieurs racines de structure plongeantes portant de nombreuses ramifications	- Type à dissymétrie aval composé d'une majorité de racines orientées vers le bas de la pente - Type pivotant composé d'une ou plusieurs racines plongeantes robustes qui pénètrent les horizons stables en profondeur
Traits racinaires potentiellement négatifs	- des racines de structure lisses, sans ramifications - de très nombreuses racines fines	- longues racines orientées vers l'amont de la pente - ramifications orientées vers le haut de la pente - sinuosités orientées vers le bas de la pente - des racines fines très nombreuses et denses
Types racinaires potentiellement négatifs	- Type latéral composé de racines de structure sub-horizontales peu robustes et de nombreuses racines fines - Type en forme de cœur composé de racines de structure obliques emprisonnant un volume de sol et avec peu de ramifications	- Type à dissymétrie amont (gravitropisme inverse) composé d'une majorité de racines orientées vers le haut de la pente - Type pivotant composé de faibles racines plongeantes formant des tapis à la surface des horizons compacts en profondeur - Type végétatif composé d'épaisses racines ou tiges souterraines sub-horizontales

CHAPITRE II

QUELLES SONT LES ESPÈCES-OUTILS LES PLUS EFFICACES POUR LA STABILISATION DES POINTS CHAUDS DE DÉGRADATION EN CHINE DU SUD ?

INTRODUCTION AU DEUXIÈME CHAPITRE

Afin d'évaluer quelles espèces sont les plus efficaces pour éviter les glissements de terrai *in situ*, il est judicieux d'examiner leur architecture racinaire, mais il est également important de considérer la biologie et l'écologie des racines, en particulier de se poser la question de la capacité des racines à survivre et à prélever des ressources dans des conditions instables. Les traits racinaires à prendre en compte deviennent alors vite nombreux et il peut être difficile de tous les prendre en compte.
Dans une première partie, seront mises en évidence les éventuelles corrélations entre traits biomécaniques et traits écologiques des racines collectées sur le site d'étude en Chine du Sud, afin d'identifier lesquels de ces traits sont les plus représentatifs des différentes fonctions importantes pour la stabilité des pentes (*Tableau 4*)

Tableau 4 : Fonctions importantes pour la stabilité des pentes et traits associés

Fonctions	Principaux traits associés
Résistance en tension	Force et contrainte maximales en tension
Elasticité	Module d'élasticité en tension
Déformation	Déformation en tension
Réversibilité de la déformation	Rapport phase élastique vs phase visco-élastique
Résistance en flexion	Rigidité en flexion
Coût de construction	Concentration en carbone, concentration en lignine
Coût de maintenance	Concentration en azote
Longévité	Concentration en carbone, en lignine, densité du tissu racinaire
Acquisition des ressources	Concentration en azote, taux de respiration, diamètre et longueur racinaire
Métabolisme	Taux de respiration

Les conditions du milieu imposent souvent des compromis et les racines ne sont pas souvent performantes dans toutes les fonctions énoncées. Les compromis mis en place sur les pentes instables de Chine du Sud seront identifiés et comparés aux conclusions trouvées dans la littérature. En effet, des traits racinaires qui sont normalement corrélés en conditions non limitantes peuvent évoluer différemment l'un de l'autre en conditions instables. Les traits racinaires à retenir pour évaluer la performance globale des racines seraient alors différents de ceux généralement admis en conditions normales. Cette sélection de traits à l'échelle de la racine ne permet toutefois pas de juger de la performance à l'échelle de la plante.
C'est pourquoi, dans la deuxième partie de ce premier paragraphe, les traits mis en évidence dans la première partie seront croisés avec des traits racinaires architecturaux. Ces traits racinaires architecturaux permettent d'intégrer les traits écologiques et biomécaniques à l'échelle du système racinaire. Une comparaison interspécifique des traits écologiques, biomécaniques et architecturaux fait ressortir les espèces qui cumulent le plus d'avantages comparatifs et qui se révèlent donc les plus efficaces sur les pentes instables de Chine du Sud. Cette sélection d'espèces peut être affinée en vérifiant si les avantages comparatifs mis en évidence pour une espèce sont conservés (i) en toutes parts du système racinaire, en particulier en profondeur et dans sa partie amont et aval par rapport à la tige, et (ii) dans des situations climatiques ou d'instabilités particulièrement défavorables, c'est-à-dire en période de mousson et en condition de glissement de terrain actif. Des préconisations peuvent être ainsi proposées, tant sur le choix d'espèces que sur la pertinence d'associations d'espèces à l'échelle du point chaud de dégradation.

II. 1. SÉLECTION DES TRAITS RACINAIRES LES PLUS REPRESENTATIFS

► Ghestem. Relationships between root traits of plants growing on unstable slopes. En préparation.

Background and aim: When assessing plant performance to resist failure during landslides, root tensile stress at failure is usually measured but other mechanical properties such as elasticity and capacity to recover after strain may also be important. Traits such as root construction cost, nutrient uptake capacity and survival should also be considered to assess the effective contribution of roots to slope stability. The aim of this study was to propose a coherent and non-redundant suite of root traits to investigate and manipulate in the future.
Methods: Mechanical, structural and chemical traits were measured on nine species present on a slope subjected to mass movement in Yunnan, China.
Main results and conclusions: We suggest concentrating on four measurements: root tensile stress, root tensile strain, nitrogen and water-soluble sugars contents. Root nitrogen content and respiration were well correlated with root mechanical resistance. This relationship may be a consequence of preferential growth in those roots which are most mechanically loaded on the slope undergoing slippage.

II. 2. IDENTIFICATION DES MEILLEURES ESPECES-OUTILS

► Ghestem, Stokes. Which plants can be used as ecological engineers to fix soil on unstable slopes? En préparation pour Restoration Ecology.

Background and aim: Reforestation programs have been initiated on wide sliding surfaces in southern China but knowledge is lacking on which plant species are the most efficient at young stages to stabilize degraded zones. This study aims at identifying which species could be used as "tools" for eco-engineering actions.
Methods: Nine species were selected at two sites: one site stabilized eight years ago by planting and a still sliding site. Stem densities were counted, young individuals were entirely hand-excavated to measure precisely their root system volume, root area density, root tensile stress and strain, root stiffness in bending, root nitrogen concentration and root water-soluble sugars at each depth and upslope and downslope from the stem. The effects of site, season, root diameter, root depth and root position from the stem were studied.
Main results and conclusions: Pueraria stricta (Leguminosae), a planted small tree native from South-East Asia, and *Artemisia codonocephala* (Asteraceae), a spontaneous biannual, seemed the most efficient species. The two species seem to be efficient even on still-sliding slopes, and are thus good candidates for slope short-term restoration. We could recommend planting or encouraging *P. stricta* at the top and *A. codonocephala* at the toe of the hotspot. We would draw practionners' attention when planting *Agava americana* (Asparagaceae) and *Jatropha curcas* (Euphorbiaciae): they do not appear to be the best candidates to stabilize slopes against landslides.

SYNTHÈSE DU DEUXIÈME CHAPITRE

Ce deuxième chapitre a pour objectif d'étudier plusieurs traits racinaires afin d'identifier, parmi les espèces présentes sur les fortes pentes de Chine du Sud, celles qui représentent les meilleurs outils pour la lutte contre les glissements de terrain. Pour ce faire, les traits racinaires à prendre en compte sont multiples et l'on a tenté d'élargir la gamme des traits étudiés par rapport aux études déjà présentes dans la littérature - traits mécaniques et architecturaux – en prenant en compte également certains traits représentatifs de l'écologie des racines. Toutefois, la prise en compte d'une multitude de propriétés racinaires peut rendre complexe la synthèse à l'échelle de l'espèce. C'est pourquoi, dans la première partie, on a étudié à l'échelle de la racine les relations entre traits mécaniques et écologiques afin de sélectionner ceux d'entre eux qui peuvent être représentatifs des grandes fonctions nécessaires pour la stabilité des pentes (*Tableau 5*). Dans la deuxième partie, quelques traits architecturaux interviennent afin d'intégrer les propriétés de l'échelle de la racine aux échelles plus larges du système racinaire et de la pente (*Tableau 5*).

Le deuxième chapitre permet de conclure sur les espèces végétales les plus efficaces pour retenir les glissements de terrain : *P. stricta* et *A. codonocephala* figurent sur le podium parmi les neuf espèces étudiées. *P. stricta* est une espèce asiatique plantée dans le cadre des programmes nationaux de reforestation. *A. codonocephala* est une espèce locale qui est connue pour ses intérêts ethnobotaniques, mais qui n'avait pas encore été identifiée comme une bonne candidate pour l'éco-ingénierie des pentes.

Tableau 5 : Traits et espèces végétales intéressants pour la stabilisation des pentes

Traits retenus pour l'évaluation des espèces	**Intérêt**
Contrainte maximale en tension	Bon indicateur pour évaluer la résistance et l'élasticité en tension
Déformation maximale en tension	Bon indicateur pour évaluer le caractère non-réversible de la déformation
Concentration en azote	Bon indicateur pour évaluer le métabolisme racinaire (capacité à exploiter les ressources du milieu)
Concentration en sucres solubles	Bon indicateur pour évaluer la fragilité de la racine
Nombre de tiges par m²	Bon indicateur pour évaluer la capacité des plantes à coloniser la pente
Volume individuel de sol exploité	Bon indicateur pour évaluer la capacité des racines à coloniser le sol
Ratio surfacique racinaire	Bon indicateur pour évaluer la densité racinaire et la proportion de racines fines:racines épaisses
Rigidité en flexion	Bon indicateur pour évaluer la résistance et l'élasticité en flexion
↓	
Espèces retenues pour la stabilisation des pentes	**Intérêt**
Pueraria stricta *Artemisia codonocephala*	Bonne espèces pour la résistance mécanique et la vivacité des racines
Chloris anomala *Jatropha curcas* *Agava americana*	Bonnes espèces pour la résistance mécanique des racines

DISCUSSION GÉNÉRALE

I. RÉPONSE AU QUESTIONNEMENT SCIENTIFIQUE

La question scientifique posée dans le titre de cette thèse - Quelles propriétés végétales influencent la stabilité des pentes ? – a été traitée en deux chapitres successifs qui ont permis d'y apporter des réponses (*Tableau 3 et tableau 5* qui synthétisent les discussions et conclusions des parties successives).

Le premier chapitre est un travail de recherche qui a permis d'approfondir des connaissances fondamentales. Les processus mécaniques par lesquels l'architecture racinaire influence la stabilité des pentes jouent sur une conjugaison des effets des racines fines et de structure qui met donc en évidence en particulier le rôle positif prédominant de la densité de ramification. L'architecture racinaire impacte les processus hydriques par la création de flux préférentiels d'eau dans la pente par les macropores créés par les racines, qui influence la création de surpressions hydriques.
Le second chapitre est un travail plus opérationnel qui a débouché sur des préconisations pratiques quant aux espèces à utiliser, à destination des forestiers chinois. Il pointe les espèces les plus efficaces pour la stabilisation des fortes pentes (*P. stricta, A. codonocephala*). Plus précisément, il met en évidence les espèces qui sont plus efficaces en haut, au milieu et en bas de point chaud de dégradation (*B. championii, C. anomala, J. curcas, P. stricta* en haut, *A. americana, A. codonocephala, B. championii* au milieu et *A. codonocephala* en bas) ainsi que celles qui sont plus efficaces pour des actions de protection de long-terme (*i. e.* qui permettent d'éviter un glissement de terrain : *A. americana, A. codonocephala, A. hispidus*) ou de restauration sur le plus court-terme (*i. e.* qui permettent de stabiliser une zone de glissement encore active : *A. americana et A. codonocephala* pour des raisons complémentaires, *B. championii et F. tikoua*) de zones dégradées.

La limite majeure de cette étude a été pointée dès l'introduction, elle réside dans le fait qu'il n'a pas été possible de vérifier les conclusions du premier chapitre sur le terrain. Il aurait été intéressant, par exemple, de mesurer la densité de ramification des systèmes racinaires excavés en Chine. Malheureusement, les scans des systèmes racinaires chinois, même s'ils étaient de qualité suffisante pour mesurer la longueur et le volume racinaires, n'étaient pas suffisamment clairs pour mesurer la densité de ramification : les ramifications se confondaient avec les croisements de racines sur les scans. L'architecture racinaire de la plupart des systèmes racinaires excavés en Chine a été mesurée manuellement en trois dimensions, du moins en ce qui concerne les racines de structure. Malheureusement, le manque de temps a empêché leur exploitation numérique.

D'autres limites de cette étude sont pointées dans la partie suivante. Des recherches bibliographiques ont été menées afin de tenter de combler les lacunes mises en évidence. Sur la base de la littérature existante à ce jour sur chacun des points exposés, des pistes de recherche sont proposées.

II. LIMITES DE LA THÈSE ET PERSPECTIVES DE RECHERCHE

II. 1. L'évaluation de l'efficacité d'une espèce : un exercice ardu

II. 1. a. Choix entre de multiples traits

Au cours de cette thèse, je me suis attachée à élargir la gamme des traits généralement pris en compte pour évaluer la performance d'une espèce au regard de la stabilisation des fortes pentes. En particulier, la première partie du second chapitre avait pour objectif de sélectionner de façon pertinente quelques traits représentatifs parmi de nombreux traits biomécaniques (14) et écologiques (9). La seconde partie du second chapitre avait pour but de regrouper ces quelques (4) traits sélectionnés avec des traits architecturaux (2) et un trait de présence sur les pentes, d'en faire une synthèse et d'identifier *in fine* les espèces les plus performantes.
Cette démarche soulève plusieurs questions. Tout d'abord, les traits initialement pris en compte sont-ils pertinents ? Sont-ils réellement représentatifs d'une meilleure stabilité des pentes ? En l'absence d'une mesure précise dans cette thèse du « niveau du trait -> niveau de l'effet » sur la stabilisation de la pente, le choix de ces nombreux traits a été justifié par des résultats présentés dans la littérature, et des hypothèses ont été posées quant à leurs effets sur la stabilité des pentes. Même si la plupart de ces hypothèses paraissent solides, par exemple le fait que la forte contrainte de résistance à la traction d'une racine augmente la stabilité de la pente, quelques-unes peuvent soulever des doutes. Par exemple, est-il vraiment bénéfique pour la stabilité des pentes que les racines soient longévives ? *A priori* il est préférable que les racines présentes dans la pente instable survivent aux perturbations. Mais, si l'espèce possède un rapide taux de remplacement (turn-over) de ses racines de façon à ne pas laisser le sol sans renforcement racinaire, des racines à très courte durée de vie peuvent avoir un effet positif sur l'enrichissement en matière organique du sol, donc peuvent accélérer la mise en place d'un sol moins sujet à l'érosion de surface et faciliter l'installation d'autres espèces, voire successions végétales (*cf* ci-dessous). Il faudrait tester chacune de ces hypothèses, c'est-à-dire la réponse de l'écosystème en terme de résistance aux glissements de terrain suite à la variation d'un trait donné, tester également l'ordre d'importance de ces réponses et leurs interactions. Pour cela, les tests en boîte de Casagrande sont intéressants. Ils permettent de tester la résistance au cisaillement d'espèces radicalement différentes sur un trait, toutes choses égales par ailleurs. C'est la démarche présentée dans le premier chapitre de cette thèse appliquée à l'étude de la réponse des traits architecturaux. Les tests en boîte de Casagrande permettent des mesures précises et facilement répétables, par contre ils permettent difficilement de mesurer les impacts du trait à tester sur le milieu et les individus voisins, à moins de planter d'autres individus autour du système racinaire à tester et de surveiller scrupuleusement les évolutions du milieu dans le temps. Il y a un compromis à accepter car les dimensions de la boîte dépassent difficilement 0.5*0.5m² de surface et 0.3m de profondeur. Si les plantes sont trop nombreuses et qu'on les laisse pousser trop longtemps dans les boîtes afin de tester l'évolution du trait et de ses impacts au cours du temps, des effets de bord peuvent apparaître qui risquent de biaiser les résultats (les racines d'accumulent sur les parois des boîtes). On peut également procéder à des tests de cisaillement *in situ* (Genet 2007), plus lourds à mettre en œuvre.
Ensuite, l'objectif final étant de faire ressortir des espèces par ordre de performance sur la stabilisation des pentes, il a fallu choisir les mêmes traits pour comparer les espèces les unes aux autres. C'est pourquoi la première partie du second chapitre a pris le parti de considérer toutes les données sans distinction d'espèces. Cependant, les relations entre traits de catégories différentes peuvent varier de façon différente d'une espèce à l'autre. Par exemple, comme indiqué dans la deuxième partie du

second chapitre, pour la majorité des espèces, la déformation ultime à la tension d'une racine ne dépend pas de son diamètre, cependant pour deux espèces (*A. codonocephala* et *P. stricta*), elle augmente avec le diamètre de la racine. La comparaison oblige au choix d'indicateurs communs (en l'occurrence a été considérée la déformation moyenne pour chaque espèce) qui ne sont pas forcément, pour chaque espèce, les plus représentatifs des fonctions recherchées. Par contre, une fois la comparaison d'espèces établie, les effets de différents facteurs – point chaud ou pente stable, saison, profondeur et position amont ou aval par rapport à la tige - sur les différents traits ont été étudiés espèce par espèce et en intégrant le diamètre racinaire comme covariable si besoin puisque le diamètre était la variable continue amenant les covariations les plus importantes dans cette étude. Cela afin d'éviter les effets « cachés ». Par exemple, une plus forte résistance à la tension des racines au mois de mai 2009 est en fait expliquée par le fait qu'en mai 2009 ont surtout été testées des racines de *A. codonocephala*, *C. anomala* et *P. stricta*, qui sont trois espèces qui possèdent, quelle que soit la saison, une importante résistance à la tension. Plus précisément, l'importante résistance moyenne à la tension des racines de *C. anomala* est en fait due au fait que pour cette espèce on a testé beaucoup de racines très fines. Il est donc important, dans l'étude des effets des facteurs sur les traits, de ne pas tirer de conclusions trop générales et de bien les étudier pour une espèce donnée et un diamètre donné.
Enfin se pose la question de la méthode d'agrégation, de synthèse ou d'intégration des traits mesurés pour en ressortir une performance « globale » de chaque espèce. La méthode la plus simple serait de sommer les valeurs des traits pour chaque espèce et de comparer les résultats. Cette méthode n'a pas de signification réelle : dans la nature, les traits ne s'additionnent pas aussi simplement. La méthode choisie dans cette thèse demeure assez simple sans être simpliste : on a d'abord combiné des traits de façon pertinente (par exemple la résistance à tension avec la densité de racines fines d'une part et la résistance à la flexion avec la densité de racines de structure d'autre part) afin d'obtenir des performances intermédiaires qu'on a ensuite sommées. Bien sûr, cette méthode, qui se justifie, n'est pourtant pas idéale. Les méthodes d'intégration de traits les plus abouties sont à trouver auprès des modélisations numériques qui relient les différents traits de la façon la plus réaliste possible à l'aide d'équations pour en tirer un résultat global. Cette méthode est au départ celle de Wu et Waldron, qui multiplient un trait architectural avec un trait biomécanique pour obtenir la cohésion additionnelle des racines. Cette relation simple a été affinée tout d'abord en sommant ce produit par classe de diamètre racinaire, puis en intégrant un terme de résistance en flexion, etc, jusqu'à parvenir à des modèles assez pointus, toujours améliorables (*cf* partie II. 3. ci-dessous). L'inconvénient de ces modèles est qu'ils nécessitent de solides compétences en mathématiques appliquées, se concentrent toujours sur les traits architecturaux et biomécaniques des racines et n'intègrent pas de traits écologiques tels que ceux étudiés dans cette thèse, à savoir la capacité d'acquisition des ressources et l'espérance de vie racinaire.

II. 1. b. L'évolution des propriétés fonctionnelles d'un individu au sein d'une communauté

Cette thèse a permis de mettre en évidence les espèces *a priori* les plus intéressantes pour la stabilisation des glissements de terrain. Cependant, un individu n'est pas seul dans son environnement, il interagit avec ses voisins, de la même espèce ou d'espèces différentes. Si la quantification de la performance d'un individu isolé n'est pas aisée (cf le paragraphe ci-dessus), la quantification de sa performance lorsqu'il est associé avec d'autres individus et la quantification de la performance globale de l'écosystème l'est encore moins. Des individus dans un même milieu ont à se partager les différentes ressources, ce qui peut amener une modification de leurs propriétés fonctionnelles.
Dans le cas précis d'un point chaud de dégradation dû à un glissement de terrain sur lequel on va tenter des actions de stabilisation d'éco-ingénierie, on peut poser comme hypothèse que les facteurs épigées – lumière, humidité ambiante, pluie - ne seront pas des facteurs limitants dans un premier temps. Le milieu est ouvert et les canopées des jeunes plants ne sont pas très hautes ni larges. Il peut

exister un effet de bord à la périphérie du point chaud où les individus sur les zones non dégradées portent leur ombre sur la zone dégradée. Mais on peut supposer que cet effet reste mineur et que les principales ressources à partager seront les ressources hypogées – nutriments, eau. Ceci est justifié par la dimension des systèmes aériens, assez restreinte, comparée à celle des systèmes souterrains, plus étendue, des individus excavés dans la deuxième partie du premier chapitre.
Les différentes interactions entre individus dans un même milieu sont de plusieurs ordres (*Tableau 6*). On pense tout d'abord à des interactions négatives telles que la compétition, le parasitisme. Mais il a été montré l'existence d'interactions neutres voire positives telles que la facilitation, le mutualisme, la symbiose.

Tableau 6 : Les différentes interactions entre espèces
c. t. : interaction sur le court terme, m. t. : moyen terme, l. t. : long terme, adapté de Bronstein (1994).

		Gain pour l'espèce A		
		Positif	**Neutre**	**Négatif**
Gain pour l'espèce B	**Positif**	Faciliation Mutualisme (c. t.) Coopération (m. t) Symbiose (l. t.)	Commensalisme	Prédation (c. t.) Parasitisme (l. t.)
	Neutre	Commensalisme	Neutralisme	Amensalisme
	Négatif	Prédation Parasitisme	Amensalimse	Compétition

Les interactions pour le partage des ressources du sol ont longtemps été considérées comme compétitives (voir Coomes & Grubb 2000) pour une synthèse bibliographique). Cette compétition est une compétition à deux sens (« two-sided competition »), c'est-à-dire que même les petits systèmes racinaires diminuent, à leur mesure, les ressources acquises par les grands systèmes racinaires, contrairement à une compétition à sens unique (« one-sided competition ») comme peut être la compétition pour la lumière dans laquelle seuls les grands individus font de l'ombre aux plus petits (Firbank & Watkinson 1987). La compétition pour le sol est également qualifiée de symétrique par rapport à la taille (« size-symetric competition »), c'est-à-dire que l'accès aux nutriments est proportionnel à la taille du système racinaire, ce qui est souvent le cas d'une ressource qui diffuse dans les trois dimensions spatiales (Cahill & Casper 2000), contrairement aux compétitions asymétriques (« asymetric competition ») par rapport à la taille comme la compétition pour la lumière qui diffuse dans une seule dimension : les plus grands individus captent toute la ressource au détriment total des plus petits. En termes de modification des systèmes racinaires, une telle compétition peut avoir pour conséquence une moindre variabilité des tailles des systèmes racinaires (Wyszomirski et al. 1999). Certains travaux ont également mis en évidence un compromis entre le volume de sol exploré et la précision de la prolifération racinaire uniquement dans les poches de sol riches en nutriments (« scale-precision trade-off hypothesis » (Grime 2007, Campbell et al. 1991), mais cette hypothèse a été réfutée par d'autres auteurs (Kembel et al. 2008, de Kroon & Mommer 2006, Kembel & Cahill 2005).
Certains auteurs ont montré que la compétition racinaire n'avait pas beaucoup d'intensité ni d'importance (voir Welden & Slauson 1986 pour les définitions de l'intensité et de l'importance d'une compétition) dans un milieu non limité en nutriments (Wilson & Tilman 1991), et qu'elle n'avait pas d'impact sur la diversité de la communauté végétale (Lamb & Cahill 2008) contrairement à la compétition aérienne (Lamb et al. 2009). Enfin, certains auteurs ont mis en évidence, plutôt qu'une compétition, une facilitation racinaire (Hauggaard-Nielsen & Jensen 2005) d'autant plus forte en milieu plus contraignant (Maestre & Cortina 2004, Callaway et al. 2002). Cette facilitation est mentionnée dans la deuxième partie du deuxième chapitre, où l'on explique que des racines se développent

préférentiellement dans les canaux racinaires mis en place précédemment par d'autres racines (White & Kirkegaard 2010, Stewart et al. 1999, Pierret et al. 1999, Kar & Ghildyal 1975). Quelques raisons expliquant cette facilitation sont énoncées.
Il n'est pas systématique que des conditions instables, qui sont une perturbation (« disturbance »), s'accompagnent d'une limitation (« stress ») des ressources (Grime 1977). Les perturbations s'accompagnent parfois de l'apparition d'un stress, mais parfois ne font que redistribuer les ressources en bouleversant les gradients écologiques en place, ce qui a pour conséquence l'apparition de zones de stress et de zones d'abondance (Myster 2001). C'est le cas des glissements de terrain (Miles & Swanson 1986, Myster & Fernandez 1995). Suite à un glissement de terrain, les gradients de ressources peuvent être redistribués de haut en bas : le haut du glissement est abrupt, instable et peu fertile, le bas du glissement est plus plat et rendu plus fertile par l'accumulation de débris (Myster & Fernandez 1995, Johnson 1976), de la périphérie vers le centre (Fetcher et al. 1996, Myster & Fernandez 1995), et/ou de façon plus irrégulière comme les zones stériles d'accumulation de roches ou au contraire les poches fertiles où demeure la végétation initiale (Velázquez & Gómez-Sal 2008, Shiels et al. 2005, Francescato et al. 2001). La surface touchée par un glissement de terrain n'est donc pas entièrement soumise aux stress ni aux perturbations ultérieures, ce qui rend encore plus difficile la quantification des relations entre systèmes racinaires.
Ainsi, il est possible que, sur les glissements de terrain étudiés dans cette thèse, les systèmes racinaires n'aient pas d'effet négatif mais un effet plutôt positif les uns sur les autres. Il s'agit ensuite d'être précis sur ce qu'on entend par « effet positif ». Dans l'objectif de la stabilisation des pentes, l'effet positif consisterait bien sûr en la propagation accélérée des individus et de leurs systèmes racinaires, mais également en l'amélioration de la résistance mécanique des racines. Ce point n'a jamais été testé à l'échelle de plusieurs individus interagissant sur le long terme. Il est également souhaitable que la facilitation racinaire augmente la capacité des racines à évacuer les surpressions interstitielles, ce qui n'a pas toujours été vérifié, au contraire (Cammeraat et al. 2005 par exemple). Se pose alors la question de la succession végétale mise en place à partir des espèces sélectionnées.

II. 1. c. La capacité d'une espèce à enclencher la succession des peuplements

Dans cette thèse, nous nous sommes concentrés sur le premier stade de succession végétale suite aux glissements de terrain. Cependant, ce stade pionnier va inévitablement évoluer. Même si la prédiction du ou des peuplements végétaux ultérieur(s) dépasse le cadre de cette thèse, il est important d'esquisser quelques pistes. Tout d'abord, il est rappelé qu'un des deux critères nécessaires pour la sélection des espèces à étudier, en supplément des dix critères additionnels, est le fait que l'espèce ne soit pas invasive sur les glissements de terrain mis à nu. Ce critère a été vérifié par la littérature et/ou par les observations de pentes dénudées proches de notre site. Il n'est donc pas à craindre une invasion par une des espèces préconisées. Sur les zones stables où la biodiversité semblait bien rétablie et les peuplements végétaux parvenus à une certaine maturité, on a relevé les espèces majoritaires suivantes : *Castanopsis delavayi*, *Coraria nepalensis* Wall., *Cotoneaster hebephyllus* Diels, *Desmodium sinuatum* Bl., *Elsholtzia winitiana* Craib, *Eupatorium adenophorum* Spreng., *Loranthus delavayi* Van Tiegh., *Pistacia weinmannifolia, Pyracantha fortuneana*, *Quercus acutissima* Carr., *Qercus aliena* var. *acute serrata* (*Figure 8-3*). Comme nous n'avons pas procédé à des relevés de végétation systématiques sur des zones altérées d'âges différents, il est difficile de détailler les stades transitoires. On peut toutefois citer les espèces intermédiaires suivantes : *Achyranthes aspera* Linn., *Cipadessa cinerascens* (Pell.) Hand., *Eupatorium adenophorum* Spreng., *Ficus semicordata*, *Paedaria foetida* (L.), *Phyllanthus emblica* L., *Pilea platanifora* C. H. Wright, *Pueraria lobata*, *Pueraria peduncularis* Grah., *Solanum verbascifolium* Linn., *Toxicodendron succedaneum*, *Trema angustifolia* (Planch.) Bl., *Vernicia fordii* (Figure 8-2). Les pentes dégradées étant interdites d'exploitation sur ce site car incluses dans des programmes de restauration nationaux, les successions sont le résultat d'évolutions principalement

naturelles, excepté le semis de *P. yunnanensis* en altitude par hélicoptère il y a quelques décennies (Sun et al. 2006) et l'entretien de *V. fordii* sur certaines parcelles où les paysans ôtent la strate herbacée et arbustive (Fattet et al. 2011).

Figure 8 : Successions végétales sur notre site d'étude.
1 : végétation rare de zone dégradée par un glissement de terrain, 2 : végétation intermédiaire, 3 : végétation plus ancienne.

Il a été montré que les successions végétales sont bien plus souvent le fait d'équilibres instables, fortement évolutifs et imprévisibles (Fukami et al. 2005, Grime 1998, Wu & Loucks 1995) que représentatives d'une dynamique attendue voire modélisable (Walker et al. 1996) vers l'installation d'un équilibre ultime et figé (« climax ») comme on l'a longtemps supposé. Ceci est d'autant plus observé dans le cas de revégétalisations - naturelles ou aidées par l'homme - suite à des glissements de terrain, perturbations qui bouleversent fortement, comme on l'a dit plus haut, le milieu initial (Myster & Walker 1997). Il serait pourtant intéressant de vérifier, voire de modéliser, le gain en stabilité des pentes tout au long de ces successions. Il est également important que ces peuplements successifs conservent d'autres avantages comme l'apport de revenus supplémentaires pour les populations locales, ce qui n'est guère le cas actuellement. Il peut donc être judicieux d'orienter ces successions par des actions humaines bien construites (Walker & Shiels 2008, Walker et al. 2007). Des idées reçues sont à présent mises en doute et il convient de surveiller de près les actions mises en place pour le long terme. Par exemple, la destruction totale de la végétation spontanée est rarement une bonne solution, même en cas d'invasion (Negishi et al. 2006, Walker 1994), la mise en place de systèmes racinaires profonds peut s'avérer dangereuse si elle n'est pas accompagnée de la mise en place d'une couverture superficielle des sols limitant l'infiltration des pluies (Ghestem et al. 2011), la pauvreté en nutriments des sols est pas un facteur plus limitant que leur instabilité pour la mise en place des pionnières (Shiels et al. 2007), mais d'un autre côté la favorisation d'espèces riches fixatrices d'azote, l'apport de litière ou de mycorhizes l'apport d'engrais peuvent bloquer la dynamique naturelle (Bardgett 2005, Walker & del Moral 2003).

II. 2. Intégration de tous les processus entre le sol et les racines

II. 2. a. Estimation des processus mécaniques

Dans cette thèse, les traits de résistance en tension et de résistance en flexion ont été pris en compte dans l'évaluation de la performance des espèces pour la stabilisation des pentes. Mais ces résistances racinaires, aussi élevées puissent-elles être, ne sont en fait d'aucune utilité si le lien sol-racine rompt rapidement. En effet, comme détaillé dans l'introduction générale de cette thèse, il existe quatre modalités de rupture du matériau sol+racines : rupture du continuum sol, rupture du contact sol-racine, rupture du contact écorce-moëlle à l'intérieur de la racine (effet « chaussette »), qui s'apparente en fait à la rupture de la racine car en aval sur la racine, c'est quand même bien souvent la moëlle qui a rompu, et enfin déformation puis rupture de la racine (moëlle) elle-même.
La rupture intervient selon la modalité qui a la plus faible résistance. Si le sol adhère peu aux racines, les racines auront beau résister en tension (résistance des liens sol-racine < résistance racinaire en tension), le glissement de terrain aura lieu quand même, avec le volume de sol glissant en aval sans les racines. Si le sol adhère bien aux racines mais que les liens internes sol-sol ne sont pas solides (lien sol-sol < liens sol-racines), le glissement de terrain aura lieu également, à partir de zones de fracture non directement localisées à l'interface sol-racine, mais au-delà, à l'intérieur du continuum sol. L'idéal est donc que la résistance des racines (en tension, en flexion, ou en flambage par compression qui est un type de flexion particulier, voire en cisaillement local, en fonction de leur orientation par rapport à la contrainte de cisaillement et de l'épaisseur de la zone de cisaillement, Mattheck 1994), soit du même ordre de grandeur que la résistance des liens sol-sol et que la résistance des liens sol-racines, tout en étant toutes les trois les plus élevées possible.
La résistance des liens sol-sol est assez facilement évaluable par les lois de la mécanique des sols telles que le critère de rupture de Mohr-coulomb. Elle dépend principalement, comme il a été expliqué dans cette thèse, des paramètres C, cohésion interne du sol et Φ, angle de frottement interne du sol. Toutefois, il est probable que la résistance des liens sol-sol augmente ou diminue avec la présence de racines, même au-delà du contact sol-racine. Plusieurs observations abondent dans ce sens. On a expliqué, dans la deuxième partie du deuxième chapitre, que la présence d'une racine modifie les propriétés biologiques, chimiques et physiques du sol dans un volume de plusieurs millimètres autour de cette racine (Ghestem et al. 2011, Fageria & Stone 2006, Pierret et al. 1999). Par la modification des propriétés du sol, la présence de racines influence la résistance d'agrégation des particules de sol. La présence des racines est généralement connue pour avoir un effet positif sur l'agrégation des particules de sol, principalement par l'augmentation de la matière organique dans les complexes argilo-humiques, qui pourrait à son tour augmenter la cohésion interne du matériau sol+racines (Fattet et al. 2011). Dans la première partie du deuxième chapitre, on a suggéré que la présence très importante de racines fines (comme dans le cas de *R. chinensis*) pourrait avoir un rôle de « fluidification » entre les particules du sol, donc diminuer l'angle de frottement interne du matériau sol+racines et aboutir à une augmentation de la résistance globale relativement peu importante. La résistance des liens sol-sol demandent de plus amples études lorsque le sol est traversé par des racines.
Les études qui prennent en compte la déformation puis rupture de la racine elle-même sous ses principales formes, tension, flexion et cisaillement local, ne sont pas nombreuses. Tosi (2007) aboutit à la conclusion que les modes de rupture en flexion et en cisaillement sont négligeables par rapport à la tension. La flexion est souvent considérée comme peu importante surtout en cas de plan de cisaillement fin (Shewbridge & Sitar 1996), mais elle est à prendre en compte en cas de zone de cisaillement plus épaisse, ce qui est souvent le cas en conditions naturelles (Thomas & Pollen-Bankhead 2010, Wu & Watson 1998). Afin de calculer la résistance en flambage par compression, qui est une flexion particulière, ces auteurs utilisent la formule d'Euler appliquée à une poutre :

$$\sigma_f = (\Pi^2 * E * I)/(L^2 * A)$$ *équation 2*

avec σ_f : contrainte en flexion (kPa), E : module d'élasticité en flexion (kPa), I : moment d'inertie de la racine (m^4), L : longueur de la racine (m), A : section de la racine (m^2).

La force de friction sol-racine est souvent considérée comme très forte (A. Favre, Ecole Centrale de Paris, comm. pers.) et donc peu importante dans l'étude des phénomènes de glissement de terrain car on considère que ça n'est pas au niveau de ces interfaces que le glissement débute (Schmidt et al. 2001). Cependant, d'autres auteurs estiment que ce mode de rupture n'est pas négligeable (Phillips et al. 2011, Schwarz et al. 2010b, Docker & Hubble 2008, Pollen 2007, Ekanayake & Phillips 2002, Abernethy & Rutherfurd 2001, Ennos 1991, Waldron & Dakessian 1981). Selon ces auteurs, beaucoup de racines glissent avant d'avoir cassé et donc il est plus important de connaître la force de friction sol-racine que la résistance maximale de la racine puisque celle-ci n'est pratiquement jamais entièrement mobilisée. La première partie du premier chapitre plaide en la faveur de cette dernière hypothèse. En effet, on a montré qu'un système racinaire composé de racines de structure avec peu de ramifications et dont les racines glissent du sol plutôt qu'elles ne cassent (*J. curcas*) apporte une résistance globale au cisaillement moindre qu'un système racinaire composé de racines de structure avec une ramification dense qui glissent également davantage qu'elles ne cassent, mais dans une moindre mesure (*R. communis*). Cependant, il est difficile de mesurer la force de friction entre une racine et le sol. Ennos (1991) propose la formule suivante :

$$S = 2 * \Pi * r * L * \tau$$ *équation 3*

avec S : force de friction sol-racine (kN), 2 π r L : surface extérieure de la racine (m^2), τ : contrainte de friction sol-racine (kPa). Cette formule a été reprise par Gray and Sotir (1996), Abernethy & Rutherfurd (2001), Phillips et al (2011), Pollen (2007), mais la difficulté est d'évaluer τ.
Suite à différentes simulations mathématiques comparées à des résultats d'expériences, Waldron & Dakessian (1981) proposent τ = 2,5 kPa.
Gray & Sotir (1996) proposent :

$$\tau = D * \gamma * (1 - \sin\Phi) * f * \tan\Phi$$ *équation 4*

avec D : profondeur de la racine, γ : densité du sol (soil bulk density), Φ : angle de frottement interne du sol et f : coefficient de friction.
Mais il reste toujours à évaluer f. Gray & Sotir (1996) estiment que le coefficient de friction entre le sol et le bois est compris entre 0.7 et 0.9 mais ne proposent pas de références bibliographiques ni expérimentales pour justifier ces valeurs. Etant donné la surface souvent rugueuse et la forme sinueuse des racines, ces auteurs fixent f = 0.9. Ce coefficient peut être évalué par des tests d'arrachement de racines individuelles (Pollen 2007, Tosi 2007, Abernethy et Rutherfurd 2001, Abernethy et al. 1999 par exemple), mais ces tests font intervenir à la fois la friction sol-racine et la résistance des racines en tension. La résistance due à la friction est d'abord très importante, puis diminue en fonction de la mobilisation de la racine en tension car celle-ci se déforme et rompt donc les liens sol-racine. Schwarz et al. (2010b) proposent une équation plus complète qui prend en compte ce caractère dynamique de la force de friction (Mickovski et al. 2007). Ils introduisent également l'augmentation de la résistance de friction due aux ramifications (Dupuy et al. 2005a, Norris 2005, Mickovski et al. 2007) :

$$S = \{[\tau * 2 * \Pi * r * (L - \Delta x)] + [\eta * (L - \Delta x)/BD]\} * f_d$$ *équation 5*

avec η : coefficient de friction additionnelle due à la présence d'une ramification, Δx : déplacement de la racine, BD : distance entre deux ramifications, (L – Δx) : longueur racinaire sur laquelle les forces de friction s'exercent, f_d : coefficient de friction dynamique.
Ils estiment que $0.1 < \eta < 5$ N par ramification supplémentaire selon l'humidité du sol et l'ordre de ramification, sans justifier ces valeurs. Ils ne donnent pas d'estimations pour f_d.
Par ailleurs, Kun et al. (2000) soulignent le fait que même lorsque la fibre (*i.e.* la racine) est rompue, il demeure une résistance de frottement entre le milieu et la fibre.
De toutes les modalités de rupture du matériau sol+racines, c'est sûrement la résistance des liens sol-racine qui est la plus difficile à calculer, alors qu'elle est certainement souvent la plus fragile des résistances et donc celle qu'il convient de pouvoir prédire et évaluer avec le plus de précision possible afin d'évaluer la résistance globale d'une pente.

II. 2. b. Interactions entre processus mécaniques et hydriques

La deuxième partie du premier chapitre montre qu'il est indispensable de prendre en compte, en plus des effets mécaniques des racines sur la stabilité des pentes, leurs effets sur les surpressions hydriques. Ces effets peuvent s'additionner ou se compenser, de façon positive ou négative pour la stabilité des pentes. Il est donc nécessaire de les prendre en compte de façon conjointe. Les études qui ont mis en évidence sur le terrain les interactions des effets hydriques et mécaniques des racines et leurs conséquences sur la stabilité des pentes sont assez nombreuses, elles sont passées en revue dans la deuxième partie du deuxième chapitre. Les études qui ont mesuré les interactions des effets mécaniques et hydriques de façon précise et qui les ont modélisées concernent surtout les effondrements de rives, où les effets hydriques étaient plus évidents (Thorne 1990). La pression matricielle du sol a généralement été mesurée de façon globale à différentes profondeurs de la rive, transformée en force, et ajoutée (en positif ou en négatif) aux forces mécaniques dues à la résistance interne du sol additionnée de la résistance apportée par les racines (Simon & Collison 2002). Dans certaines études, les pressions hydriques dans les macropores ont été mesurées distinctement de la pression matricielle (Collison & Anderson 1996), mais ces mesures ont été ensuite moyennées par tranche de profondeur en prenant en compte la densité moyenne de macropores dans le sol étudié. Calculés ainsi de façon homogène sur la masse du sol, les effets hydriques des racines sont souvent bien supérieurs aux effets mécaniques (Simon & Pollen 2004), même pour de jeunes plants âgés de 2 ans (Pollen et al. 2004). Des avancées ont permis de prendre en compte dans ces calculs la variabilité spatiale et temporelle de la pression matricielle et des propriétés géotechniques du sol (Pollen 2007). Cette thèse a mis en avant la nécessité de prendre en compte également la variabilité spatiale des résistances ou fragilités mécaniques et hydriques dues aux racines. En effet, les racines forment un réseau interconnecté le long duquel agissent des effets positifs ou négatifs sur la stabilité des pentes qui ne peuvent être intégrés de façon homogène à l'échelle d'une masse de sol, mais qui doivent être calculés et intégrés localement suivant l'organisation spatiale des racines dans le sol.

II. 3. La modélisation numérique pour une quantification intégrée

II. 3. a. Représentation 3D des résistances mécaniques

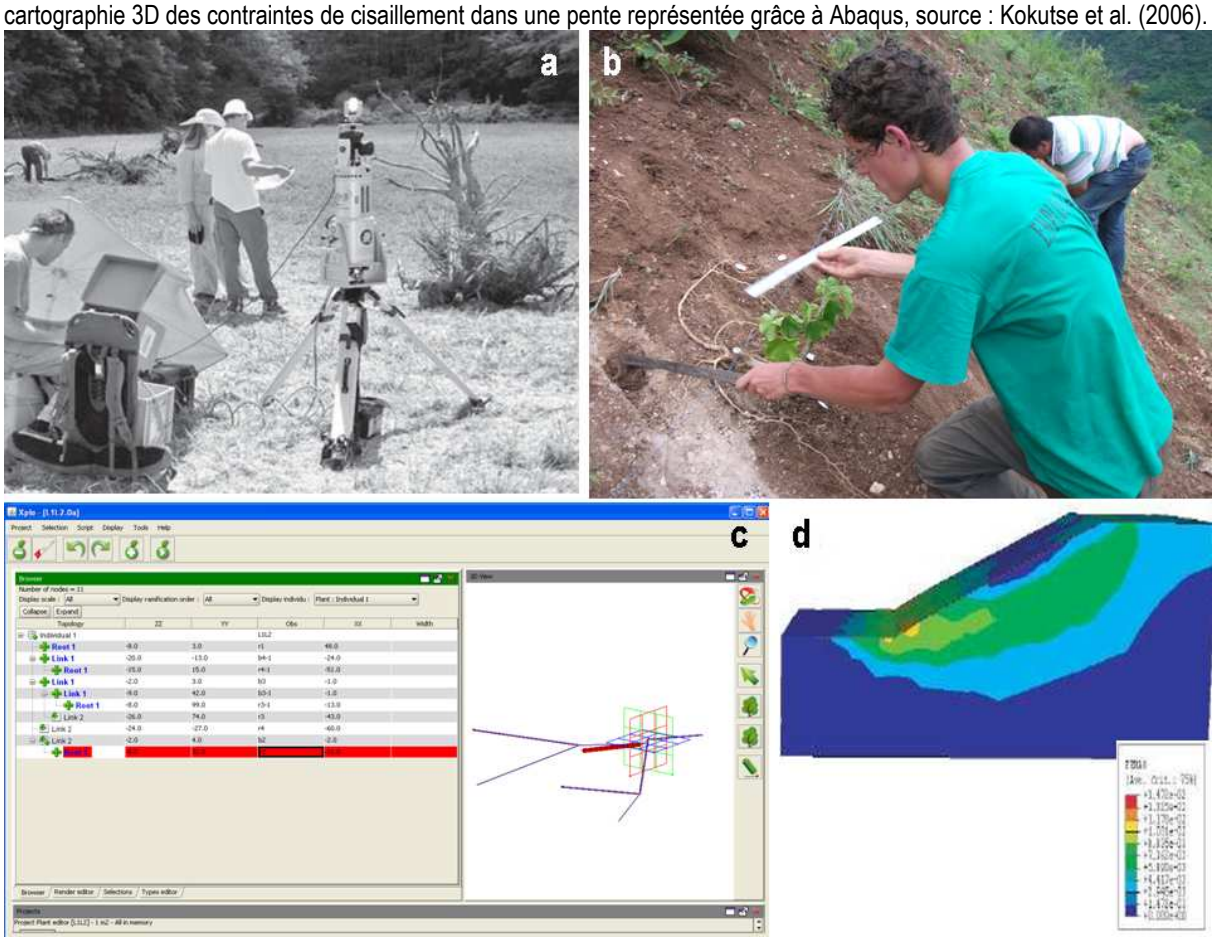
Les mathématiques appliquées et la modélisation numérique sont de bons outils pour la résolution de calculs complexes et la visualisation des phénomènes. Ces outils ont permis d'explorer en détail la résistance au cisaillement de racines en deux dimensions (dans le sens du cisaillement).

► Mickovski, Fourcaud, Stokes, van Beek, Ghestem. 2011. Simulation of direct shear tests on rooted and non-rooted soil using Finite Element analysis. Ecological Engineering 37: 1523-1532. doi: 10.1016/j.ecoleng.2011.06.001

Cependant, cette thèse met en évidence la nécessité de prendre en compte l'organisation spatiale des racines en trois dimensions pour un calcul pertinent de la stabilité d'une pente. Il existe différentes méthodes pour digitaliser des structures en 3D, en particulier des systèmes racinaires excavés (Zanetti et al. 2008). Une méthode est d'utiliser un numériseur magnétique qui enregistre les coordonnées de points remarquables : les points de ramifications, les extrémités de racines… (Danjon et al. 1999a & b, *figure 9a*).
Lorsqu'on ne dispose pas de cet équipement coûteux, on peut mesurer manuellement les coordonnées (x, y, z) des points remarquables ou les caractéristiques (longueur, orientation, inclinaison) des éléments racinaires (*Figure 9b*) et les entrer dans des outils à interface conviviale qui permettent la visualisation 3D des systèmes racinaires et surtout la transformation de ces données en langage informatique « mtg ». Parmi ces outils libres d'accès, il existe Archiroot (Dupuy 2003), www.archiroot.org.uk) et Xplo (http://amapstudio.cirad.fr, figure 9c). Des requêtes existent en mtg grâce au logiciel Amapmod (Danjon et al. 1999 a & b, Godin et al. 1997) qui permettent d'extraire de nombreuses propriétés architecturales à partir de ces systèmes 3D, par exemple la longueur racinaire totale en fonction de la profondeur… Ces outils de digitalisation 3D ont été utilisés tout d'abord pour la quantification de traits racinaires et leur corrélation à des mesures de résistance du système racinaire, en l'occurrence de résistance au vent (« overturning », Danjon et al. 2005). C'est la démarche suivie dans la première partie du premier chapitre de cette thèse pour la résistance au cisaillement cette fois, mais la quantification des traits racinaires étudiés dans cette thèse n'a pas nécessité l'utilisation de digitalisation 3D. On comprend ici que la digitalisation 3D, qui demande des mesures fastidieuses et un long travail d'analyse informatique, ne se justifie pas toujours. Par exemple, Danjon et al. (2007) ou Ghestem et al. (2009) dans le cas d'études de la résistance de systèmes racinaires au cisaillement ont digitalisé ou numérisé différents systèmes racinaires en trois dimensions, mais en ont ensuite extrait des valeurs de RAR (root area ratio) selon deux dimensions : amont et aval de la pente par rapport au collet pour ensuite les intégrer dans une méthode de calcul de stabilité des pentes en deux dimensions (Slip4Ex, Greenwood 2006, est un logiciel 2D simple et gratuit pour calculer le facteur de stabilité d'une pente, ou FoS, factor of safety).

► Ghestem, Stokes, Cao, Ma, Xie. 2009. Using vegetation to stabilize steep slopes in Southern China: Root biomechanics as a factor in the choice of species. Thibault, B. (Ed). Proceedings of 6th Plant Biomechanics Conference. Cayenne : 450-455.

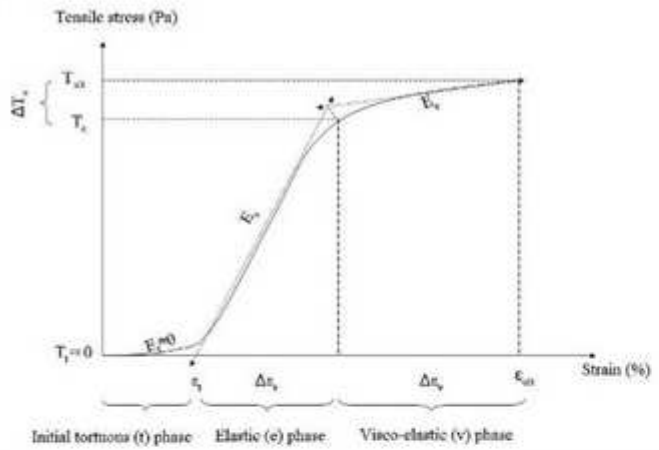
Figure 9 : Méthodes de numérisation des systèmes racinaires
a) mesure d'un système racinaire à l'aide d'un numériseur magnétique, source : Zanetti et al. 2008 ; b) mesures manuelles, source : M. Ghestem ; c) système racinaire d'un *B. championii* représenté grâce à Xplo, source : M. Ghestem ; d) cartographie 3D des contraintes de cisaillement dans une pente représentée grâce à Abaqus, source : Kokutse et al. (2006).



Par contre, la digitalisation 3D se justifie lorsqu'on s'en sert pour des calculs de résistance en trois dimensions. C'est le cas de l'étude menée par Dupuy et al. (2007) dans le cas de résistance au vent : les systèmes racinaires ont été mesurés et digitalisés en trois dimensions, puis intégrés dans le logiciel Abaqus (Abaqus Inc., http://www.abaqus.com/) qui permet des calculs de résistance en trois dimensions selon la méthode des éléments finis (*Figure 9d*). Une telle démarche appliquée aux glissements de terrain est en cours dans le cadre du projet CATARS (bourse CNRS-CEMAGREF Ingénierie écologique) qui implique le CEMAGREF de Grenoble, de Aix en Provence et AMAP, et qui comporte également une comparaison entre les méthodes de calcul par éléments finis et par éléments discrets (Kneib 2011). Les systèmes racinaires 3D sont intégrés dans le sol modélisé comme des éléments aux propriétés mécaniques constantes : elles sont soit considérées comme des éléments indéformables, soit caractérisées par un module d'élasticité constant et identique pour toutes les racines. Or, comme détaillé dans cette thèse, la plupart des racines se déforment selon trois phases (mise en tension puis phase élastique et phase visco-élastique le cas échéant) avant la rupture. La courbe contrainte-déformation propre à chaque racine peut être formulée en équations en fonction de l'espèce et du diamètre de la racine (*Figure 10*).

Figure 10 : Mise en équation des courbes contrainte-déformation
pour chaque espèce en fonction du diamètre de la racine considérée, d'après les données collectées en Chine du Sud. a) représentation graphique d'une courbe contrainte-déformation d'une racine soumise à une force de tension, pour d'avantage d'informations, se référer au Chapitre 2, partie 1 ; b) liste des abbréviations utilisées ; c) formulation des équations des courbes pour chacune des neufs espèces chinoises étudiées.

a



b

Phase	Abbreviation	Meaning
Straightening	ε_t (%)	Strain of tortuosity
Elastic phase	E_e (MPa)	Modulus of elasticity
	$\Delta\varepsilon_e$ (%)	Increment of strain during the elastic phase
	F_e (N)	Tensile load at the end of the elastic phase
	T_e (kPa)	Tensile stress at the end of the elastic phase
Visco-elastic phase	E_v (MPa)	Modulus of visco-elasticity
	$\Delta\varepsilon_v$ (%)	Increment of strain during the visco-elastic phase
	ΔF_v (N)	Increment of tensile load during the visco-elastic phase
	ΔT_v (kPa)	Increment of tensile stress during the visco-elastic phase
Failure	ε_{ub} (%)	Ultimate strain at root breakage
	F_{ub} (N)	Ultimate tensile load at root breakage
	T_{ub} (kPa)	Ultimate tensile stress at root breakage
Curve shape	E_v/E_e (%)	Modulus of visco-elasticity on modulus of elasticity ratio
	$\Delta\varepsilon_v/\Delta\varepsilon_e$ (%)	Increments of strains during the visco-elastic phase on elastic phase ratio

c

Tortuosity phase

1)	*A. americana*	$T=0$ till $\varepsilon=\varepsilon_t=$ 2.59
2)	*A. codonocephala*	$T=0$ till $\varepsilon=\varepsilon_t=$ 2.99
3)	*A. hispidus*	$T=0$ till $\varepsilon=\varepsilon_t=$ 2.23
4)	*B. championii*	$T=0$ till $\varepsilon=\varepsilon_t=$ 1.03
5)	*C. anomala*	$T=0$ till $\varepsilon=\varepsilon_t=$ 2.62
6)	*F. tikoua*	$T=0$ till $\varepsilon=\varepsilon_t=$ 2.30
7)	*J. curcas*	$T=0$ till $\varepsilon=\varepsilon_t=$ 1.64
8)	*P. stricta*	$T=0$ till $\varepsilon=\varepsilon_t=$ 2.48
9)	*R. chinensis*	$T=0$ till $\varepsilon=\varepsilon_t=$ 0.80

Elastic phase

1)	then $T=E_e*(\varepsilon-\varepsilon_t)$	and $E_e=$	aD^{-b}	with a=	310	and b=	0.85	till $T=T_e=$	aD^{-b}	with a=	16.02	and b=	0.64
2)	then $T=E_e*(\varepsilon-\varepsilon_t)$	and $E_e=$	aD^{-b}	with a=	383	and b=	1.01	till $T=T_e=$	65.89				
3)	then $T=E_e*(\varepsilon-\varepsilon_t)$	and $E_e=$	aD^{-b}	with a=	317	and b=	0.24	till $T=T_e=$	22.07				
4)	then $T=E_e*(\varepsilon-\varepsilon_t)$	and $E_e=$	aD^{-b}	with a=	371	and b=	0.51	till $T=T_e=$	22.01				
5)	then $T=E_e*(\varepsilon-\varepsilon_t)$	and $E_e=$	aD^{-b}	with a=	406	and b=	1.03	till $T=T_e=$	aD^{-b}	with a=	18.98	and b=	0.96
6)	then $T=E_e*(\varepsilon-\varepsilon_t)$	and $E_e=$	482					till $T=T_e=$	23.31				
7)	then $T=E_e*(\varepsilon-\varepsilon_t)$	and $E_e=$	aD^{-b}	with a=	137	and b=	-0.67	till $T=T_e=$	6.05				
8)	then $T=E_e*(\varepsilon-\varepsilon_t)$	and $E_e=$	aD^{-b}	with a=	877	and b=	0.85	till $T=T_e=$	aD^{-b}	with a=	53.27	and b=	0.54
9)	then $T=E_e*(\varepsilon-\varepsilon_t)$	and $E_e=$	aD^{-b}	with a=	127	and b=	0.63	till $T=T_e=$	5.89				

Visco-elastic phase

1)	then $T=T_e+[E_v*(\varepsilon-\varepsilon_t+\Delta\varepsilon_e)]$	and $E_v=$	aD^{-b}	with a=	97	and b=	0.78	till $T=T_{ub}=$	$a*D^{-b}$	with a=	21.03	and b=	0.68
2)	then $T=T_e+[E_v*(\varepsilon-\varepsilon_t+\Delta\varepsilon_e)]$	and $E_v=$	aD^{-b}	with a=	164	and b=	0.60	till $T=T_{ub}=$	$a*D^{-b}$	with a=	32.11	and b=	0.74
3)	then $T=T_e+[E_v*(\varepsilon-\varepsilon_t+\Delta\varepsilon_e)]$	and $E_v=$	414					till $T=T_{ub}=$	$a*D^{-b}$	with a=	25.18	and b=	0.20
4)	then $T=T_e+[E_v*(\varepsilon-\varepsilon_t+\Delta\varepsilon_e)]$	and $E_v=$	921					till $T=T_{ub}=$	$a*D^{-b}$	with a=	26.05	and b=	0.64
5)	then $T=T_e+[E_v*(\varepsilon-\varepsilon_t+\Delta\varepsilon_e)]$	and $E_v=$	aD^{-b}	with a=	280	and b=	0.47	till $T=T_{ub}=$	$a*D^{-b}$	with a=	33.75	and b=	0.82
6)	then $T=T_e+[E_v*(\varepsilon-\varepsilon_t+\Delta\varepsilon_e)]$	and $E_v=$	962					till $T=T_{ub}=$	42.44				
7)	then $T=T_e+[E_v*(\varepsilon-\varepsilon_t+\Delta\varepsilon_e)]$	and $E_v=$	aD^{-b}	with a=	454	and b=	-0.69	till $T=T_{ub}=$	$a*D^{-b}$	with a=	9.70	and b=	-0.50
8)	then $T=T_e+[E_v*(\varepsilon-\varepsilon_t+\Delta\varepsilon_e)]$	and $E_v=$	aD^{-b}	with a=	27	and b=	0.94	till $T=T_{ub}=$	$a*D^{-b}$	with a=	56.31	and b=	0.55
9)	then $T=T_e+[E_v*(\varepsilon-\varepsilon_t+\Delta\varepsilon_e)]$	and $E_v=$	aD^{-b}	with a=	353	and b=	0.72	till $T=T_{ub}=$	$a*D^{-b}$	with a=	9.38	and b=	0.33

Il serait donc intéressant, dans les études futures, d'attribuer ces propriétés mécaniques aux racines composant le système racinaire (possible dans Xplo) afin de calculer ensuite les champs de résistance en trois dimensions à partir de comportements racinaires plus réalistes. Un autre obstacle à surmonter est la modélisation des liens sols-racines dont il a été question ci-dessus. Actuellement, les modélisations considèrent que les racines ne glissent pas, elles sont ancrées en tout point à l'élément de sol contigu (Kneib 2011). Afin de représenter la réalité de façon plus correcte, un coefficient de friction pourrait être introduit le long des racines.

II. 3. b. Représentation 3D des évolutions de la pression hydrique

Les effets hydriques des racines sur la stabilité des pentes sont du même ordre de grandeur que leurs effets mécaniques et les compensent même parfois, mettant en péril la stabilité de la pente (cf ci-dessus, Simon & Collison 2002 par exemple). On a montré dans cette thèse l'intérêt de prendre en compte l'organisation spatiale des racines en trois dimensions pour l'étude des écoulements et de leurs effets sur la stabilité des pentes. La modélisation 3D des écoulements dans des macropores s'est d'abord attachée à quantifier les flux de façon réaliste dans des pores individuels linéaires puis dans des pores individuels de géométrie différente (pore obstrué, pore avec une ramification, pore discontinu..., Tsutsumi et al. 2005). La matrice et les macropores sont deux milieux dans lesquels les écoulements ne sont pas formulés de la même façon (équations de Richards et équations de Manning respectivement), cependant ces deux régimes d'écoulement interagissent et il a été montré qu'il existe un seuil de saturation au-delà duquel les macropores deviennent hydrologiquement actifs et exportent l'eau de façon plus rapide que la matrice. En-deça de ce seuil, les macropores sont évités par les écoulements qui se cantonnent à la matrice (Nieber et al. 2006). Nieber & Sidle (2010) prennent en compte la densité, la distribution, l'orientation, la taille et le risque d'érosion interne des macropores correspondant à ce qui est mesuré sur le terrain afin de calculer les flux matriciels et intra-pores. Ces études parviennent à des conclusions en termes de flux hydriques, qu'il conviendrait de convertir en pressions hydriques. Ainsi, il serait possible de superposer les modèles 3D architecturaux, mécaniques (dont il est question dans la partie précédente) et hydriques en termes de contraintes. On aboutirait à des cartographies 3D de contraintes « mécaniques + hydriques » qui permettraient d'identifier les zones de plus grande fragilité. En effet, une succession de zones fragiles contiguës est susceptible d'initier un glissement de terrain.

II. 3. c. Evolution temporelle des effets des racines sur la stabilité des pentes

En plus de l'organisation spatiale en trois dimensions des effets des racines sur la stabilité des pentes, il est important de pouvoir prendre en compte leur évolution temporelle. L'évolution temporelle se situe à deux échelles de temps distinctes. D'une part, les systèmes racinaires ne sont pas des structures inertes et les racines croissent, même à une vitesse assez lente. D'autre part, comme il a été mentionné dans la partie précédente, les réseaux hydriques dans les macropores ne sont pas statiques non plus et varient dans le temps, en particulier avec le niveau de saturation de la matrice. Ces variations de régime hydrique peuvent être assez rapides surtout en cas de fortes pluies répétées.
Les modèles numériques simulant la croissance racinaire sont nombreux (voir Bonneu 2011 pour une revue complète). Ils ne sont pas toujours dynamiques dans le sens où certains peuvent donner une prédiction du système racinaire à un moment t sans décrire le système racinaire aux temps intermédiaires de 0 à t. Parmi les modèles de croissance, il existe des modèles de structure, *i.e.* qui donnent une prédiction de la croissance des racines elles-mêmes, on obtient donc une visualisation de la structure (topologie et géométrie) du système racinaire. Ils intègrent explicitement les trois principaux processus racinaires : la croissance, la mortalité et la ramification. Il existe également des modèles de

densité, qui ne prédisent pas la structure du système racinaire, mais des répartitions spatio-temporelles de densités comme la densité des apex racinaires. Certains d'entre eux intègrent les principaux processus racinaires de croissance, mortalité et ramification. Ils présentent l'avantage d'être moins lourds en calculs (Bonneu et al. 2011).

Il ne serait pas pertinent de coupler un modèle dynamique de croissance racinaire et un modèle dynamique de flux hydrique, les pas de temps ne sont pas identiques. Par contre, il peut être judicieux d'envisager le calcul de l'architecture racinaire en trois dimensions par un modèle de croissance racinaire (pas de temps : le mois ou l'année), de le figer à un temps donné (par exemple : début de saison des pluies), d'en extraire une cartographie 3D des résistances mécaniques et de coupler cette cartographie statique avec un modèle dynamique de variation spatiale des résistances hydriques (pas de temps : la minute ou l'heure) qui permette de faire apparaître les zones de fragilité critiques au sein de la pente durant des épisodes de fortes pluies par exemple.

CONCLUSION

Cette thèse a permis d'identifier les espèces les plus efficaces pour retenir les fortes pentes de Chine du Sud et de montrer l'intérêt de l'étude de l'architecture racinaire dans la compréhension des phénomènes déclenchant les glissements de terrain.

Elle a mis en évidence des points nouveaux :
- la seule présence de racines n'est pas suffisante pour augmenter la résistance du sol au cisaillement : il existe des organisations racinaires privilégiées (première partie du deuxième chapitre)
- la présence de racines peut avoir des effets hydriques négatifs sur la résistance du sol au cisaillement (deuxième partie du deuxième chapitre)
- les compromis de croissance racinaire ne sont pas les mêmes sur pentes propices aux glissements de terrain qu'en terrain non perturbé et non limitant (première partie du premier chapitre)
- les espèces largement utilisées dans les programmes de reforestation des pentes ne sont pas les meilleures candidates pour éviter les glissements de terrain (deuxième partie du premier chapitre)

Ces points nouveaux améliorent la compréhension des processus intervenant dans la stabilité de pentes instables, mais ils ajoutent également à leur complexité. De ce fait, certains points n'ont pas été étudiés, qui constituent les limites de cette thèse : l'étude des interactions entre systèmes racinaires dans l'espace et dans le temps et les méthodes de calcul des effets racinaires dans l'espace et dans le temps pour aboutir à une estimation pertinente de la stabilité d'une pente donnée à un moment donné. Des pistes pour des recherches futures, consolidées par la littérature existante, ont été proposées.

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ANNEXES

ARTICLES COMPOSANT LA THÈSE

Chapitre I

Partie I. 1.

► Ghestem, Veylon, Bernard, Vanel, Stokes. Influence of root system morphology and architectural traits on soil shear resistance. Prêt pour Plant and Soil.

Influence of root system morphology and architectural traits on soil shear resistance

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Abstract

Background and Aims: Vegetation can be used to stabilise slopes with regard to shallow landslides, but the optimal plant architecture for conferring resistance is not known. This study aims at identifying root morphological traits which confer the most resistance to soil during shearing.

Methods: Three species (*Ricinus communis* L., *Jatropha curcas* L. and *Rhus chinensis* Mill.) were grown in large shear boxes for 10 months. Direct shear box tests were then performed on the rooted soil and compared to fallow soil. Root systems were excavated and a large number of traits measured.

Results: Shear strength and deformation energy were enhanced by the presence of roots. Regardless of confining pressure, *R. communis* conferred most resistance to shear due to its taprooted system with many vertical roots. *J. curcas* possessed oblique and vertical roots which might have created fragile zones through soil profile. The least efficient root system

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with regard to resisting shear, was *R. chinensis* which possessed many horizontal lateral roots. Soil mechanical properties were most influenced by (i) density of roots crossing the shear plane, (ii) branching density throughout soil depth, (iii) total length of coarse roots above the shear plane and (iv) total volume of coarse roots and fine root density below the shear plane. During failure, fine, short and branched roots slipped through soil rather than breaking.

Conclusion: Root morphological traits such as root density, branching, length, volume inclination and orientation can influence significantly soil mechanical properties.

Key words: soil reinforcement, soil cohesion and friction angle, *Jatropha curcas* L., *Ricinus communis* L., *Rhus chinensis* Miller, slope stability, landslides.

Nomenclature

Abbreviations

A	aerial parts of the plants
BD	root branching density (Nb of branches mm^{-1})
bw	backward to the shear direction
cR	coarse roots
CSA	cross sectional area (mm^2)
D	root density (g mm^{-3})
d	dry
diam	root diameter (mm)
DL	dead leaves
F	fruit
fR	fine roots
fw	forward to the shear direction
GL	green leaves

inf	below the shear plane
L	root length (mm)
m	mass (g)
MC	moisture content (%)
Mdiam	root mean diameter (mm)
Nb	number
perp	perpendicular to the shearing direction
$p\eta^2$	partial η-squared statistical indicator
shp	shear plane
S	stem
sup	above the shear plane
V	root volume (mm^3)
v	soil volume (mm^3)
w	wet
0-30°	root inclination from 0° (horizontal) to 30°
30-60°	root inclination from 30° to 60°
60-90°	root inclination from 60° to 90° (vertical)

2. Symbols

c'	effective cohesion of the material (kPa)
γ	tangential displacement (mm)
J	total energy per unit shear area and unit displacement ($J\ m^{-2}\ m^{-1}$ = kPa)
ε	tangential strain (%)
ε_{yield}	tangential strain at yield point (%)
T	tangential force (N)

Φ'	effective internal friction angle of the material (°)
G	shear modulus (kPa)
ρ_d	soil dry bulk density (g cm^{-3})
ρ_w	soil wet bulk density (g cm^{-3})
σ_n	normal stress at yield point (kPa)
τ	tangential shear stress (kPa)
τ_{res}	residual tangential stress (kPa)
τ_{yield}	tangential shear stress at yield point (kPa)

Introduction

Landslides are defined as a mass movement of soil or debris with gravity as the main cause, hydrological causes often being a secondary cause (Sidle and Ochiai 2006). The use of vegetation to reinforce soil on landslide-prone slopes is an ecological and economical alternative to traditional civil engineering methods (Stokes et al. 2009). To identify useful species, it is necessary to measure well-defined, measurable properties, or traits, of organisms at the individual level and use them comparatively across species (McGill et al. 2006). With regard to slope stability, the most important plant traits are those belowground, as the morphology and topology of plant root systems influence strongly the resistance of soil to shearing during a landslide. Root architectural traits are probably more important than root mechanical traits with regard to the additional cohesion conferred on soil by roots (Endo & Tsuruta 1969; Docker and Hubble 2008; Mao et al. in press), although the tensile strength and stiffness (high modulus of elasticity) are major traits governing the additional cohesion provided by roots to soil (Genet et al. 2005; Mickovski et al. 2007 a and b).

To quantify the contribution of roots to a given soil's shear resistance, it is possible to carry out direct shear tests on soil with and without roots (Casagrande 1936; Barnes 1995). Direct

shear tests of soil blocks have been conducted in the field (Endo 1980; O'Loughlin and Ziemer 1982; Nilaweera 1994; Wu and Watson 1998; Greenwood et al. 2004; Cammeraat et al. 2005; van Beek et al. 2005) and in the laboratory (Waldron 1977; Waldron and Dakessian 1982; Gray and Ohashi 1983; Shewbridge and Sitar 1989; Abe and Ziemer 1991a and b; Wu and Watson 1998; Operstein and Frydman 2000; Cazzuffi et al. 2006; Fan and Su 2008a and b; Fan and Chen 2010; Loades et al. 2010; Mickovski et al. 2011). During the soil shearing process, the shear strength of a soil embedded with real roots, or fibre inclusions, increases with the number of roots (Kaul 1965; Kassif and Lopelovitz 1968; Manbeian 1973; Ziemer 1981a and b; Abe and Iwamoto 1986 and 1990). These studies also showed that soils containing roots with a range of orientations develop wider shear zones and can slowly mobilize reinforcement from roots *via* their tensile strength even at large shear displacements (Wu and Watson 1998). The orientation of those roots will also ordain which roots act in tension or in compression. Thomas and Pollen-Bankhead (2010) distinguished the mechanical behaviour of roots during a landslide in that those which are oriented upslope fail in shear and those which grow downslope bend and then shear.

During shear failure of a root-permeated soil in the field, in root systems which possess numerous, spreading, highly-branched fine roots with a relatively high tensile strength e.g. *Acacia floribunda* (Vent.) Willd., roots break progressively and a high stress peak is obtained during failure. However, in the case of root systems e.g. *Eucalyptus amplifolia* Naudin, which present only a few, large, non-branching vertical roots concentrated directly beneath the tree stem with relatively low tensile strength, the maximum stress is low and no sharp stress peak is observed during failure (Docker and Hubble 2008). In tests carried out on five plant species grown in shear boxes and subjected to shear, it was found that root systems with oblique and vertical roots e.g. *Leucaena leucocephala* (Lam.) de Wit confer more resistance to shear than root systems where lateral roots are dominant e.g. *Hibiscus tiliaceus* L. (Fan and Chen 2010).

125 The failure mode for roots deep in the soil is not the same as for those at the surface: deeper
126 roots tend to slip out of the soil whereas roots near the surface are more likely to break under
127 tension (Mickovski et al. 2008).
128 Although the mechanism by which individual roots fail during shear has been well described
129 (Hathaway and Penny 1975; Cofie et al. 2000; Cofie and Koolen 2001; Genet et al. 2005);
130 Bischetti et al. 2005 and 2009); several questions remain with regard to the behaviour of
131 entire root systems placed under shear. Which root system traits are able to increase the zone
132 of shear, and hence improve shear resistance of a soil? Does the presence of roots in a soil
133 block alter soil physical properties e.g. strain at maximum shear stress, modulus of elasticity,
134 residual stress, total deformation energy, cohesion and internal friction angle? These
135 parameters are important to evaluate the resistance of root-permeated soils, which should be
136 as high as possible, but also the deformation before rupture and the energy that root-
137 permeated soils can absorb (Ekanayake and Phillips 1999). It is also important to determine
138 and quantify the susceptibility of roots to break rather than slip because their tensile strength
139 is fully mobilized in case of breakage, not slippage. Assuming that all roots break at the same
140 time leads to overestimations of numerical models estimating slope stability (Docker and
141 Hubble 2008). Inherent soil cohesion and internal friction angle properties have also been
142 found to be modified by root growth through soil, but the mechanism by which roots can alter
143 these physical properties remains unknown (Operstein and Frydman 2000; Graf et al. 2009;
144 Fattet et al 2011). To investigate these questions, we performed shear tests on blocks of soil in
145 which three species had been grown: *Jatropha curcas* L., *Ricinus communis* L. and *Rhus*
146 *chinensis* Miller. These species are used in reforestation programs in Southern China where
147 landslides are common (Ghestem et al 2009; Stokes et al. 2010). We determined not only the
148 maximal shear stress due to the presence of roots, but also the strain at maximum shear stress,
149 modulus of elasticity, residual stress, total deformation energy, cohesion and internal friction

angle (Fig. 1). After the test, root systems were excavated and morphological traits quantified. Results are discussed with regard to how different root system architectures can confer mechanical reinforcement to soil along a slope.

Material and methods

Conception of shear boxes

To perform shear tests on live plants, thirty 0.5 m long x 0.5 m wide x 0.3 m deep boxes were built from 7 mm thick PVC. As the root-soil matrix inside these boxes was to be sheared during testing, it was necessary for the two halves of the boxes to be separate so that they could slide over each other during testing. Therefore, boxes were composed of two parts, one stacked on top of the other (Fig. 2a). Each part was attached to the other with PVC plates held in place with nuts and bolts. To prevent soil dropping out of the boxes, a 10 mm thick plate was attached to the bottom half of the box. Holes were drilled every 0.05 m along the plate, allowing water to drain freely out of the box.

Soil characteristics

The substrate chosen for growing plants was similar to that found in the Yunnan province, China, where all three species are found (Ghestem et al. 2009; Fattet et al. 2011). An alluvial silty clay from Aix-en-Provence, France with a textural composition of 41% clay, 48% silt and 11% sand (textural analysis obtained by sedimentation and sieving, NF P 94-056 and NF P 94-057, Afnor 1996) was found to be similar to the Chinese soil (46% clay, 48% silt, 6% sand; Ghestem et al 2009; Fattet et al 2011). Before sowing seeds, soil was placed inside each shear box at a dry bulk density of 1.38 g cm^{-3} and 15% water content, corresponding to soil conditions found *in situ* in Yunnan in August 2009 (1.31 g cm^{-3} dry bulk density and 15%

water content, (Ghestem et al. 2009). Thus each box weighed 112 kg. Stones and debris were removed during compaction.

With regard to shear resistance of the two soil types, we determined effective soil cohesion, *C'*, and soil effective internal friction angle *Φ'*, on French soil using direct shear tests (NF P94-070, Afnor 1996): strain-controlled direct shear tests were carried out on reconstituted, drained 60mm x 60mm x 20mm soil samples with roots and stones removed during the reconstitution process. Samples were not saturated prior to testing, and as they were kept sealed at 4°C after removal from the field, it can be assumed that soil moisture content was similar to that in field conditions. Samples were placed in a shear testing device (VJTech 2760A, U.K.) and normal loads of 200, 300 and 500 N were applied as confining pressure on three separate samples taken from the same block of soil. A lateral displacement was applied at a speed of 0.013 mm s^{-1} until failure occurred and the peak shear force recorded. Results showed that French soil possessed a mean *C'* of 26.79 kPa and a mean *Φ'* of 20.58°, similar to that of the Chinese soil at same dry bulk density (31.68 kPa and 32.11°, unpublished data).

Plant materiel and growth conditions

Three species found on steep slopes in western Yunnan (Ghestem et al. 2009; Fattet et al. 2011) were chosen: *Jatropha curcas* L., *Rhus chinensis* L. and *Ricinus communis* Miller. *J. curcas* and *R. communis* are trees which originate from South America and tropical Africa, respectively. These species are planted as crops in southern China, as their seeds are used for the production of biofuel. *R. chinensis* is a native tree found on steep slopes in the Yunnan province. Seeds were scarified by wet and cold conditions between wet cottons in a fridge at 4°C for at least 2 months. Seeds were then placed at ambient temperature for germination. After germination, to facilitate initial growth, seedlings were planted in 300 cm^3 pots filled with compost. When plants were 15 to 30 days old, they were carefully transplanted into the

198 shear boxes (Fig. 2a), without disturbing soil around the root system. A total of nine plants
199 per species were grown and three boxes filled with soil were left intact (with no plants), to act
200 as controls. Boxes were placed outside in May 2010 at a nursery in Aix en Provence, southern
201 France, and irrigated using a drip system. Shear boxes were painted white to reflect sunlight
202 and prevent soil temperatures from rising too high (Fig. 2b). In November 2010, a transparent
203 plastic tunnel was set up around the plants to protect them from low temperatures. In March
204 2011, all boxes were carefully transported to the laboratory for testing.
205

206 ## Shear tests

207 Before testing, shoot height, canopy width and stem basal diameter (Collar diam) were
208 measured. Arial parts (A) of the plant were split into green leaves (GL) and dead leaves (DL),
209 stem (S) and fruits (F) if any, were collected and dried at 60° C until constant mass (m). Soil
210 height in the shear box was measured to determine if soil compaction had occurred during
211 plant growth and irrigation. The box was then weighed to estimate the soil wet bulk density
212 (ρ_w). The shear box was carefully placed inside the direct shear box (NF P 94-071-1; Afnor
213 1996; Lambe and Whitman 1979; Fig. 2c) using an electrical winch. The plates connecting
214 the upper and lower halves of each shear box (Fig. 2a) were then removed and a square
215 wooden plate placed on the soil surface. A confining pressure was applied by placing a weight
216 on top of the wooden plate. Three masses were chosen: 20, 50 and 100 kg corresponding
217 respectively to initial normal stresses of 3.5, 4.7 and 6.8 kPa at the shear plane. The maximal
218 normal mass, 100 kg, was chosen to represent the loading which can be found on a densely
219 vegetated slope, assuming that the aboveground parts of a given adult tree weigh
220 approximatly 500 kg (the range of values for these data is wide, but an average order of
221 magnitude is several hundred kg for an adult tree, Kenzo et al. 2009, Yamakura et al. 1986)
222 and act upon a 1.0 m² root plate. The resulting pressure would therefore be 500 kg * 9.81

223 $N.kg^{-1}$/1.0 m^2 ~ 5 kPa. This mass can also be considered in terms of additional depth above
224 the shear plane, 100 kg representing approximatively 0.3 m of soil of dry bulk density of 1.38
225 g cm^{-3}. The total shear depth would thus be 0.6 m, which is in the order of magnitude of
226 landslide and root presence depths. The minimal normal mass was only 20 kg, representing an
227 almost bare slope and ensuring a minimal confinement pressure during the test. For each
228 confining pressure, three repetitions were carried out, resulting in nine tests per species.
229 However, for two *R. chinensis* plants, growth was poor and roots did not always traverse the
230 shear surface and one test also failed due to a technical error. Therefore, data for six tests only
231 are available for this species. For fallow soil, no repetitions were performed at each normal
232 mass. Tests were carried out a speed of 8.33 10^{-3} mm s^{-1} (minimal speed possible with this
233 apparatus) and total lateral displacement was fixed at 110 mm.
234 From load-displacement curves obtained during the shear test, we calculated stress-strain
235 curves taking into account the decreasing shear plane area during the test (Fig. 1a). Direct
236 shear box tests are interpreted as quasi-simple shear with an unknown shear zone width
237 (Shibuya et al. 1997):

238 $$\tau = T/[0.487*(0.487-\gamma)]. \quad \text{Eq. 1}$$

239 and

240 $$\varepsilon = \gamma/0.487 \quad \text{Eq. 2}$$

241 τ is the tangential shear stress (kPa), T is the measured tangential force (kN), γ is the
242 tangential displacement (m), ε is the tangential strain, 0.487 m is the internal width and length
243 of the box.

244 In stress-strain curves where the maximum shear stress was not indicated by a clear peak at
245 soil rupture, the yield point was chosen as the inflexion point of the curve, as it represents a
246 transition between elastic and plastic behaviour. Thus the term “yield” is preferred to the term
247 “maximum” when referring to data at failure. From the stress-strain curve obtained for each

248 test, we estimated the maximum shear stress ($\tau_{,yield)}$ and strain (ε_{yield}) at soil failure, as well as
249 the shear modulus (G), residual stress ($\tau_{,res}$) and total deformation energy (J).

250 Henceforth, these five parameters are named "*mechanical properties*" for each block of
251 fallow soil or soil embedded with roots.

252 G was calculated using the initial slope value of the stress-strain curve:

253 $$G = \Delta\tau / \Delta\varepsilon \qquad \text{Eq. 3}$$

254 After failure occurs, the shear resistance converges toward an asymptotic value called the
255 residual tangential stress (τ_{res}). Constant residual stress is not always obtained, therefore in
256 our study, residual tangential stress (τ_{res}) was measured at strain = 16%. Total deformation
257 energy (J) is the quantity of energy necessary to displace a block of soil to its yield point and
258 was calculated as the area below the stress-strain curve until the yield point:

259 $$J = \int_{x=0}^{x=0.487} \tau(x)\, d\gamma(x) \qquad \text{Eq. 4}$$

260 Effective soil cohesion (c') and effective internal friction angle (Φ') were calculated using the
261 Mohr-Coulomb failure criterion (Amar and Magnan 1980, Fig. 1b)

262 $$\tau_{yield} = c' + \sigma_n * \tan\Phi' \qquad \text{Eq. 5}$$

263 where σ_n is the normal stress (i.e. confining pressure) at yield point, c' is the origin ordinate
264 and $tan\Phi'$ the slope of the Mohr-Coulomb criterion curve.

265 To measure soil dry bulk density (ρ_d) and soil moisture content (MC), two small blocks of soil
266 were removed from above and below the shear surface, as well as at the shear surface, i.e. in
267 total six blocks per box. Each small soil block was weighed (wet mass m_w), dipped in hot
268 paraffin to seal it, then immersed in water to measure its exact volume (v) and eventually
269 weighed after drying at 105°C until constant weight (dry mass m_d, NF X31-510, Afnor 1996).

$$\rho_d = m_d / v \quad \text{Eq. 6}$$

$$MC(\%) = (m_w - m_d) * 100 / m_d \quad \text{Eq. 7}$$

Root system morphology

After each test soil was carefully removed from around each root system. We defined coarse roots (cR) as being structural roots which were thicker, stiffer and longer than fine roots (fR), but no specific diameter class was chosen to separate coarse and fine roots. Thus, coarse roots had large diameters (diam) than fine roots but not necessarily < 2 mm, which is a size class often used to distinguish fine and coarse roots (Stokes et al. 2009). For each coarse root, we measured diameter at its origin, shear plane and end (which was not always the apex if the root had broken), as well as total length (L) and branching density (BD = number of branches/root length) above (sup) and below (inf) the shear plane (shp), root azimuth at its origin and at the shear plane (fw: roots growing in the direction of shear, bw: roots growing away from the direction of shear and perp: perpendicular to the shearing direction, Fig. 2d), root angle with regard to the horizontal at the origin of the root and also when it traversed the shear plane (Fig. 2e). Root angle was divided into three categories (Fig. 2e): roots growing at an angle between 0 to 30° were termed horizontal or lateral roots; roots growing at an angle between 30° to 60° were oblique roots, and those found at an angle between 60° to 90° were termed vertical roots. Coarse vertical roots emerging from the collar were called taproots whereas finer vertical roots emerging from lateral roots were named sinker roots. We calculated coarse root volume (V) assuming that each root was cylindrical. Coarse root mean diameter (Mdiam) above and below shear plane was determined by dividing root volume by its length. We also counted the number (Nb) of coarse roots traversing the shear plane.

To measure the quantity of fine roots, soil blocks (approximately 10 cm x 10 cm x 10 cm) were removed from the different sectors (fw, bw and both perp sectors, Fig. 2d) in the shear box, both above and below the shear surface, resulting in 12 soil blocks per box. These soil blocks were weighed. From this fresh weight and the fresh bulk density, we were able to obtain the volume of each sample. Fine roots were extracted from the sample and dried at 60°C until a constant weight was reached. Fine root densities per unit of soil (g cm^{-3}) were calculated as root dry weight/soil volume. By multiplying this density by the volume of half-boxes, we obtained fine root mass (m) above and below shear plane. The mean diameter of fine roots (Mdiam) at the shear plane was also calculated. The total cross sectional area (CSA) was calculated for fine and coarse roots crossing the shear plane, assuming that roots were circular.

We also noted if the root was broken or had slipped through the soil, in order to examine if the mode of failure (breakage or slippage) was determined by architectural traits. The breakage/slippage observations were linked to Mdiam, to Lsup, BDsup, root azimuth and angle. Only Lsup and BDsup were taken into account because finding the distal part of a broken root in the soil was not feasible. Concerning root mode of failure, data are missing for *R. chinensis* due to experimental errors.

Statistical analysis

Relationships between σ_n, ρ_w, MC and mechanical properties of each box were investigated using Pearson's correlations. In case of mechanical properties correlated with σ_n, in order to remove the σ_n effect, we calculated:

$$\Delta Y_{i,j} = Y_{i,j} - Y_{fallowsoil,j} \quad \text{Eq. 8}$$

where Y is one of the mechanical properties, i is 1, 2 or 3 for each species and j is 1, 2 or 3 for each normal stress and $\Delta Y_{i,j}$ was used instead of $Y_{i,j}$ for the subsequent analyses. Pearson's correlations were also used to investigate relationships between MC and plant aerial parts (Am, GLm, DLm, Sm and Fm), and to investigate relationships between mechanical properties and architectural traits. To study which architectural variables influenced most mechanical properties, we considered all species together because we did not have enough data to analyse each species individually. Therefore, we were able to determine which suite of root architectural traits enhance most shear resistance on a slope with a mixture of species present, as often found in southern China (Fattet et al. 2011).

Each time a significant correlation was found, we plotted the corresponding graph to verify that the significance was not only due to extreme data. Linear regressions were carried out to determine c' and Φ'.

Each time parametric tests were used to relate the effect of treatments on variables, the following assumptions are checked: residuals were independent, they possessed homogeneous variance (homoscedasticity) and they were identically distributed following the normal law of mean = 0 and variance = σ^2. If these assumptions were not met, non-parametrical tests were used. Mann-Whitney non-parametric tests were carried out to compare mechanical properties between two independent groups: fallow and rooted soils, so as to identify the effect of root presence and broken or pulled-out roots, to investigate if the mode of failure depended on Mdiam, L or BD. To compare the number of broken roots and pulled-out roots in each azimuth and each inclination for each plant, non-parametric Wilcoxon matched-pair tests were performed. Anova and Ancova parametrical tests (type III) were performed to investigate species effect on mechanical properties, with MC as a covariate if needed. Tukey Honestly Significant Difference (HSD) post-hoc tests were used to discriminate among

species. The partial η-squared indicator ($p\eta^2$) was used to compare effect size between MC and species.

Principal component and classification analysis (PCA) was used to group individuals with regard to root morphological data. Assumptions required to proceed to a correct PCA were checked (Roberts and Everson 2001; Abdi and Williams 2010), i.e. the determinant |R| of correlation matrix between variables was not too low (in a singular matrix there is a linear combination between several variables), |R| was not equal to 1 (in an identity matrix all variables are orthogonal and correlations null) and that each variable has a substantial correlation with at least one other variable. Individuals with too large a contribution to an axe were observed and removed from the analysis if needed.

Data are shown as mean ± standard error (s.e.)

Results

Shear tests

The mechanical behaviour of each rooted soil block during shear testing appeared to differ depending on species. In fallow soil, a build up of soil occurred at the front of the shear box. After tests on *R. communis*, zones of loosely packed soil in front of the root system were found and hollows of loose soil behind the root system were noted.

The shape of the stress-strain curves also differed between species. In fallow soil and for the species *J. curcas* and *R. chinensis*, the curves displayed no marked yield point. Only in *R. communis* was failure of the soil-root matrix indicated by a clear peak for $\sigma_{\tau,yield}$ (Fig. 3). For the majority of the curves, shear stress continued to increase progressively after rupture of the soil-root matrix.

Regardless of species, mechanical properties were not correlated with σ_n except τ_{res} (r=0.77, p<0.001, Fig. 4). Therefore, for the following results, $\Delta\tau_{res}$ will be taken instead of $\tau_{,res}$ ($\Delta\tau_{,res}$ was not correlated with σ_n). Regardless of species, mechanical properties were significantly and negatively correlated with MC ($\tau_{,yield}$: r=-0.65, p<0.001; γ_{yield}: r=-0.49, p=0.009; *E*: r=-0.53, p=0.005; $\Delta\tau_{,res}$: r=-0.62, p=0.001; *J*: r=0.60, p=0.001). Within a given species, no significant relationships between mechanical properties and MC existed. MC was negatively correlated with Am (r=-0.44, p=0.022) and GLm (r=-0.49, p=0.010). GLm was significantly different between species ($F_{3, 23}$=9.78, p<0.001), *R. communis* having significantly more green leaves (8.62 ± 1.89 g) than *J. curcas* (0.16 ± 0.16 g) and *R. chinensis* (3.75 ± 1.00 g).

Regardless of confining pressure, MC and species, τ_{yield} and *J* were significantly higher in rooted soils compared to fallow soils (Fig. 4a, e, $Z_{24,3}$=2.27, p=0.02). The effect of root presence on ε_{yield} was almost significant (Fig. 4b, $Z_{24,3}$=1.74, p=0.08), but there was no significant linear influence on *E* (Fig. 4c). With regard to τ_{res}, which depends on σ_n, data were too few to carry out a statistical analysis taking into account the three different confining pressures.

When mechanical properties were compared between species, it was found that all mechanical properties were significantly greater in *R. communis* compared to *J. curcas* and *R. chinensis* (Fig. 4, τ_{yield}: $F_{2,21}$=13.49, p<0.001; ε_{yield}: $F_{2,21}$=4.67, p=0.021; *G*: $F_{2,21}$=12.56, p<0.001; $\Delta\tau_{res}$: $F_{2,21}$=8.05, p=0.002; *J*: $F_{2,21}$=8.00, p=0.003). All mechanical properties were slightly higher for *J. curcas* than for *R. chinensis*, but differences between these two species were not significant (Fig. 4). When mechanical properties were compared between species with MC as a covariate, the species effect was more important (higher $p\eta^2$) than MC effect (lower $p\eta^2$; Table 1).

If we attempt to determine *c'* and Φ' parameters, we can observe that the linear relationship was significant only for *J. curcas* (Fig. 4a, $\tau_{yield}=0.053+1.29*\sigma_n$, $r^2=0.62$, $p=0.01$), as variability was too high in the remaining two species.

Root system morphology

PCA showed that from the projection of morphological characteristics on the plane composed by the two first explanatory axes (Fig. 5a), four major groups of traits appeared. The first axe was positively correlated with fine root data i.e., fR_{sup} D, fR_{shp} D, fR_{inf} D, BD_{sup}, BD_{inf}. This axis was negatively correlated with Collar diam, cR_{sup} Mdiam, cR_{shp} Mdiam, cR_{inf} Mdiam, $cR_{sup\ 60\text{-}90°}$ V. Therefore, when the first axis is positive, it describes the abundance of fine roots and when negative it represents the presence of large diameter and deep tap roots. The second axe was positively correlated with $cR_{shp,60\text{-}90°}$ CSA and $cR_{inf,60\text{-}90°}$ V. This axis was negatively correlated with $cR_{shp,0\text{-}30°}$ CSA, $cR_{shp,30\text{-}60°}$ CSA, $cR_{inf,0\text{-}30°}$ V, $cR_{inf30\text{-}60°}$ V, $cR_{sup,0\text{-}30°}$ V. Therefore, when positive, this axis describes the presence of sinker roots and when negative it describes the abundance of horizontal and oblique roots.

From the projection of cases on the 1 x 2 factor-plane (Fig. 5b), three well-separated groups appear which correspond clearly to the three species, demonstrating that the three species possess different root system morphologies (Fig. 6):

- *J. curcas* has a large stem-root base from which few large and deep tap roots emerge. Sinker and lateral coarse roots are few, and fine roots are not abundant;

- *R. chinensis* has a thin stem-root base and long sub-horizontal branched roots with many fine roots;

- *R. communis* has a large stem-root base which tapers rapidly and from which several highly branched long sinkers emerge, with many fine roots.

Relationships between root morphological traits and soil shear resistance

All correlations between root system morphological characteristics and mechanical factors were positive, showing that roots improve soil shear resistance. In the upper part of the shear box, cR_{sup} L was significantly correlated with τ_{yield}, G, $\Delta\tau_{res}$ and J; BD_{sup} was significantly correlated with τ_{yield}, G and $\Delta\tau_{res}$; and $cR_{sup,fw}$ D was significantly with ε_{yield}. At the shear plane, fR_{shp} m and cR_{shp} Nb were significantly correlated with all five mechanical properties. $cR_{shp,60\text{-}90°}$ CSA was significantly and positively correlated with τ_{yield}, ε_{yield} and E and $cR_{shp,fw}$ CSA was significantly correlated with $\varepsilon_{yield.}$ Below the shear plane, fR_{inf} m was significantly correlated with τ_{yield}, G, and J, cR_{inf} V was significantly correlated with τ_{yield} , ε_{yield}, and J, $cR_{inf,perp}$ V was significantly correlated with τ_{yield} , ε_{yield}, $\Delta\tau_{res}$ and J and BD_{inf} were significantly correlated with τ_{yield} and G (Table 2).

In *J. curcas*, slipped roots were significantly more numerous than broken roots, whatever their azimuth, except in the perp sector. Oblique roots significantly slipped out of the soil rather than break (Table 3). In vertical and horizontal roots, they tended also to slip out of the soil but no significant trend was obtained (Table 3). In *R. chinensis* no significant differences were found in the numbers of broken and slipped roots, regardless of orientation or angle. In *R. communis*, only fw roots and horizontal roots slipped significantly rather than break (Table 3). Mdiam of broken roots was significantly higher than that of slipped roots in *J. curcas* (Table 4). The result was similar in *R. communis* but not significant. In *R. chinensis*, broken and pulled-out roots possessed identical Mdiams (Table 4). In both *J. curcas* and *R. communis*, L_{sup} of broken roots was significantly greater than that of slipped roots, whereas BD_{sup} of slipped roots was significantly higher than that of broken roots (Table 4).

Discussion

Root system types and efficacy to prevent against landslides

In this study, individuals of 10 months old and grown in an environment similar to that found in the Yunnan province, China, can be considered as young individuals of species used in slope rehabilitation programs in southern China.

R. communis appears to be the species which most enhances mechanical parameters influenced by the presence of roots. *R. communis* possesses long, vertical coarse roots throughout the root system, which act together as a lever arm, which can efficiently resist shear. High branching densities anchor the root system and many fine roots cement the soil material. This result is similar to that found by Thomas and Pollen-Bankhead (2010) modelling the resistance of root bundles.

Although Fan and Chen (2010) found that plant root systems with many oblique and vertical roots were highly efficient for resisting shear, we found that in *J. curcas* root systems, which possessed oblique and vertical roots, resistance to shear was lower than that of *R. communis*. Roots were thicker, shorter and less numerous in *J. curcas* compared to *R. communis*. Coarse roots possess larger surface areas that can be fragile if root-soil bonds are weaker than soil-soil bonds. If branching density is low and fine roots are few, smooth and straight coarse roots slip more easily out of the soil. It is also likely that in root systems with oblique and vertical roots, a volume of soil is trapped within the roots, which is difficult to mobilize. Even if it crosses the shear plane, this soil volume is protected by the surrounding structure of coarse roots and does not necessarily contribute to shear resistance.

R. chinensis possessed many fine roots and thin, long horizontal structural roots. Many fine roots can contribute to soil cohesion by increasing soil carbon content and soil aggregate stability (Fattet et al. 2010). However, it is also possible that a high number of fine roots can reduce soil consolidation through disaggregation, or by influencing water retention (J.

457 Nespoulous, pers. comm.) In our study, soil moisture was negatively correlated with the mass
458 of aerial parts and in particular with the mass of green leaves e.g. *R. communis* had low soil
459 moisture and highly resistant soil mechanical properties. *R. chinensis* and *J. curcas* possessed
460 higher soil moisture contents but less resistant soil mechanical properties. As all plants
461 received the same amount of water via irrigation during the same plant growth period,
462 differences in soil moisture are likely due to plant evapotranspiration. Therefore, our study
463 suggests that in field conditions, local hydrological conditions around individuals will differ,
464 influencing in turn soil mechanical properties. In an environment where the three species
465 would be subjected to the same levels of precipitation and temperature, evapotranspiration
466 would likely be higher in *R. communis*, due to its larger leaves, rendering soil drier and more
467 mechanically resistant when held in shear. Yet, in a case of a heavy monsoon rain,
468 evapotranspiration effect may be too slow to counteract rain falls. Interactions between
469 hydraulic and mechanic effects of roots in the soil are complex and worth more studying
470 (Ghestem et al. 2011).
471 Caution needs to be taken when translating laboratory results to field conditions. *R. communis*
472 and species with a similar type of root system could be promoted as efficient species to
473 stabilise steep slopes. Nevertheless, the root system of *R. communis* is not wide-spreading and
474 in the field, it would not occupy as much underground space as other root systems e.g. *R.*
475 *chinensis* or *J. curcas*. On fragile slopes, practitioners should avoid leaving non-rooted
476 volumes between plant individuals (Genet et al 2008).

477 **Architectural traits**

478 At the shear plane, root number was correlated with mechanical properties whereas no
479 significant relationship was found between root CSA and mechanical properties. Therefore,
480 bundles of roots were more determinant than their cumulative CSA (Pollen and Simon 2005;
481 Schwarz et al. 2010; Mao et al. 2011). Coarse roots act more in bending (in the forward

direction) and when they are oriented vertically, compared to when they are horizontally aligned and act in tension (in the backward direction).

Even when the shear plane is forced and constrained as in our direct shear tests, architectural traits above and below the shear plane can play an important role on soil mechanical properties. Coarse root length or volume, together with branching density either above or below the shear plane allow for the development of a dense root net. Above the shear plane, coarse roots act more in bending (towards the direction of shear) but below the shear plane, the coarse roots which contribute most to shear resistance are those perpendicular to the shear direction, possibly because deep roots are mobilized later during the test, when fw roots do not act any more. Hence, below the shear plane, coarse roots act more like anchors.

Branching density throughout soil depth has been shown to govern root anchorage in given situations (Dupuy et al 2005a; Mickovski et al. 2007a and b). We show that densely branched roots slip out of the soil rather than break. Fine and short roots slip out of the soil rather than break, as in agreement with Ennos (1990) studying leek seedlings, but contrary to results of shear tests carried out by O'Loughlin and Ziemer (1982) on beech (*Nothofagus*) forest-covered soil. *J. curcas* roots slip rather than break whatever their angle and orientation, possibly due to a creation of fragile zones around coarse roots in this species. In *R. chinensis*, where roots also slip rather than break, numerous fine roots exist, thus decreasing the root-soil bond. In *R. communis*, root modes of failure were more complex depending on root angle and orientation. Roots oriented away from the direction of shear, *i. e.* roots mobilized in tension during the first stages of the shear process, broke rather than slipped. These roots thus resisted failure until they reached their ultimate tensile strength. Roots oriented towards the direction of shear and perpendicular to it, i.e. roots mobilized in bending during the secondary stages of the shear process, slipped rather than broke. These roots resisted shear in bending and their ultimate resistance was not fully mobilized until the late stages of the test, causing a high

507 residual stress. Roots inclined horizontally slipped rather than broke because they were
508 mostly fine roots. However, vertical roots coarse roots broke rather than slipped, causing a
509 large fully mobilized resistance against shear stress.
510 All modes of failure should be considered when estimating the additional shear strength
511 conferred by roots, depending on their angle and orientation. Future research should combine
512 both the mechanical properties of roots with the three dimensional structure of root systems.
513 Such an approach is emerging in studies on tree anchorage with regard to overturning (Dupuy
514 et al. 2007) and landslides (Kokutse et al. 2006, Danjon et al 2008).

515 **Stress-strain curves and soil mechanical properties**

516 In our study, an increase in shear stress after the yield point was found in fallow soil, which
517 was likely an artefact due to a build up of soil at the front of the shear plane. Ekanayake and
518 Phillips (1999) showed that in shear tests on fallow and rooted soils, sharp and well-defined
519 peaks occurred in the stress-strain curves in fallow soils, but broader and flatter peaked curves
520 occurred in tests on rooted soils. Docker and Hubble (2008) explain that, in rooted soil, this
521 increase in shear stress after the yield point can be a consequence of the action of roots which
522 continue to confer resistance to shear, either because they are not all broken or because they
523 still provide friction even if they are broken. According to them, no-peak curves correspond to
524 tests where many roots have not yet broken and are yet to mobilise their full tensile strength.
525 These authors also suggest that large test displacements enable a peak to be reached even for
526 no-peak type curves. However, if no-peak type curves represented a less advanced stage of
527 the peak type curves, we would have obtained several curves with peak well distributed all
528 over the strain range. In our study, either the peak occurred within the first 7% of strain, or it
529 never occurred. We believe that the type of curve is more representative of soil rheological
530 properties. Peak-type stress-strain curves usually occur in consolidated soils, whereas curves
531 without a peak appear to occur in unconsolidated soils.

Docker and Hubble (2008) propose that peak-type curves are usually found in root systems possessing many fine roots spread over the failure plane, causing failure in the manner of a soil-root matrix with higher apparent cohesion, rather than by a greater anchoring mechanism which is at the other end of the cohesion-anchoring spectrum. In our observations, peak-type curves were likely due to an anchoring mechanism such as in *R. communis* root system, close to to tap-root system), compared to a well-distributed fine rooted system e.g. *R. chinensis*, which can be named a "lateral-type root system. *J. curcas* is close to the "heart-shaped root system type", which can be considered as a combination of tap-root systems with lateral root systems. This disparity in curve shape between rooted/ fallow soils and species may be due to differences in the interaction between soil physical properties and root system morphology. Only would a large number of tests on plants in a variety of soils enable us to elucidate the relationship between soil shear resistance and root morphological traits.

We showed that the effect of roots on shear stress at yield point is significant, as also shown by Docker and Hubble (2008), Fan and Su (2008) and Operstein and Frydman (2000). Shear strain at yield point was enhanced to a lesser extent, partly because its location is not obvious, especially on a non-peaked curve. Nor is it clear if a short or a long shear strain helps prevent against landslides. Certain authors have concluded that soil with roots is mobilized at a larger shear displacement than fallow soil but the position of the peak on non-peaked curves is not always clearly explained (Docker and Hubble 2008, Operstein and Frydman 2000, Ekanayake and Phillips 1999, Waldron 1977, Manbeian 1973). Ekanayake and Phillips (1999) suggest that the longer the shear strain, the better to prevent against landslides because it allows sufficient time for the soil stresses to reduce (e.g., during drainage) before a complete failure occurs. However, in direct shear tests, soil and roots are confined in a box of limited dimensions, but in natural conditions during a landslide, there are fewer obstructions to prevent soil sliding away from roots. Soil particles can only bear short strains, as shown by

557 the fallow soil tests. Thus, even if soil-root bonds can deform to high strain levels and thus
558 retain the soil contiguously to the roots, soil located further away from roots will likely break
559 at shorter strains. We suggest therefore, that the faster a rooted soil can reach peak stress, the
560 higher the soil resistance to landslides because it will be able to rapidly counteract sliding
561 stresses without significant deformation.

562 **Effect of confining pressure on soil effective cohesion and internal friction angle**

563 Confining pressure was not correlated with tangential stress at yield point. Therefore, there
564 was no justification for us to derive the Mohr-Coulomb criterion of failure (Amar and
565 Magnan 1981). The tangential stress-normal stress graph (Fig. 4a) shows that in *R. communis*,
566 data were highly scattered and that the presence of roots was more significant than that of
567 confining pressure. In *R. chinensis*, only one data point was available at low normal stress,
568 and so it was not possible to determine the effect of confining pressure. However, in *J. curcas*,
569 the linear regression between confining pressure and stress at yield point was significant and
570 suggests a significant increase in internal friction angle and a decrease in effective soil
571 cohesion close to no-cohesion properties. These data would confirm that our tests were
572 performed in a range of low confining pressures, where Mohr-Coulomb linear criterion is not
573 relevant and should be replaced by a non-linear failure envelope (Alonso et al. 1990; Fig. 1b).
574 Our study shows that soil strength does not necessarily increase with normal load (or
575 increasing depth, Terwilliger and Waldron 1990) and that data may not necessarily be
576 interpreted as evolutions in soil cohesion and friction angle. For all these reasons, we make an
577 interpretation of shear resistances rather than shear strength parameters *c'* and Φ'. To obtain
578 significant results with regard to soil effective cohesion and friction angle, we would have had
579 to apply higher confining loads, but which in turn may have masked the influence of roots on
580 soil mechanical properties. Nor would higher confining loads have represented natural field
581 conditions where confining pressures are lower.

582 We also showed that effective soil cohesion and internal friction angle obtained from small
583 soil samples (NF P94-070, Afnor 1996) are not necessarily comparable to results from large
584 shear boxes. This disparity is likely due to differences in soil texture, structure, soil moisture
585 and compaction or confining load which are much more homogenised in small samples than
586 in larger boxes (Terwilliger and Waldron 1990).
587

588 ## *Conclusion*

589 Root systems of three species: *J. curcas*, *R. communis*, *R. chinensis* were tested in a large
590 Direct Shear Box to investigate the effects of root presence and root architecture on resistance
591 to shear processes. The following conclusions emerge:

592 - during shear process, roots act positively on shear yield stress and deformation energy, less
593 significantly on shear strain, and have no significant effect on soil elasticity and residual
594 stress, this latter property depending more on confining pressure and soil moisture (soil
595 intrinsic properties) than on root presence;

596 - *R. communis's* tapering root system increases shear properties more than *J. curcas'* heart
597 and *R. chinensis'* lateral root systems because *R. communis'* sub-vertical coarse roots act like
598 a strong lever against shear and its rather numerous branches and fine roots tightly anchor the
599 root system above and below the shear plane. Nevertheless, this conclusion has to be
600 transposed to the field with caution because *R. communis'* root system is narrower than other
601 root systems and may not colonize slope soil as efficiently as other species;

602 - all species considered together, roots not only present at shear plane but also above and
603 bellow shear plane increase shear resistance. Cross sectional area is not the most efficient root
604 trait to increment shear resistance, but other root traits such as root number and branching
605 density shall be considered;

- all modes of failure combined with root inclination and orientation shall be considered when calculating additional cohesion brought by roots.

Root traits may not be efficient if they are considered one apart from the others: *J. curcas'* coarse roots and *R. chinensis's* fine roots are not as efficient as a mixture of the two (*R. communis*) and could even have ambivalent effects which have to be verified on effective shear resistance of soil. That is why root architecture is interesting: it considers root architectural traits and their organisation. Even if the conclusions about root mitigated effects on shear resistance are delicate because data are not many, this study suggests future research to persevere in the understanding of the - positive or negative- mechanical impacts of roots against landslides.

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Tables

Table 1

Comparison between species and moisture content (MC) effects on mechanical properties. Partial eta-square ($p\eta^2$) indicates the effect strength.

	Species effect			MC effect		
	$F_{2,20}$	p	$p\eta^2$	$F_{1,20}$	p	$p\eta^2$
τ_{yield}	7.75	0.011	0.36	0.46	0.505	0.02
ε_{yield}	2.58	0.100	0.20	4.36	0.050	0.19
G	6.40	0.007	0.39	0.40	0.534	0.02
J	6.40	0.007	0.40	0.40	0.534	0.03
$\Delta\tau_{res}$	3.30	0.058	0.25	4.36	0.050	0.18

794 Table 2

795 Values of significant ($p<0.05$) coefficients of correlation (r) between architectural traits and mechanical properties

	Correlated traits	$\sigma_{\tau,yield}$	$\varepsilon_{\tau,yield}$	G	$\Delta\sigma_{\tau,res}$	E
Traits above the shear plane	cR_{sup} L	0.57		0.61	0.54	0.46
	$cR_{sup,\ fw}$ V		0.49			
	BD_{sup}	0.57		0.65	0.52	
Traits at shear plane	fR_{shp} m	0.71	0.43	0.66	0.48	0.60
	cR_{shp} Nb	0.60	0.43	0.59	0.50	0.54
	$cR_{shp,\ fw}$ CSA		0.43			
	$cR_{shp,\ 60\text{-}90°}$ CSA	0.48	0.52			0.57
Traits below the shear plane	fR_{inf} m	0.56		0.52		0.51
	cR_{inf} V	0.44	0.45			0.55
	$cR_{inf,\ perp}$ V	0.61	0.41		0.48	0.65
	BD_{inf}	0.48		0.66		

796

797

798 Table 3

799 Mean value ± s. e. of number of broken and slipped roots counted in the different azimuths and at different angles for the three species. Values

800 with different letters are significantly different at $p<0.05$.

Architectural traits	Species and mode of failure					
	J. curcas (n=9)		*R. chinensis* (n=6)		*R. communis* (n=9)	
	broken roots	slipped roots	broken roots	slipped roots	broken roots	slipped roots
	8.2 ± 1.4 a	17.8 ± 3.3 b	36.3 ± 9.5	32.7 ± 12.7	21.0 ± 5.1	26.7 ± 4.6
Root azimuth						
bw	3.5 ± 0.7 a	6.0 ± 1.3 b	19.3 ± 3.2	16.7 ± 8.2	11.4 ± 3.2	8.7 ± 1.8
fw	2.2 ± 0.7 a	5.9 ± 1.1 b	17.0 ± 7.2	16.0 ± 4.5	4.6 ± 1.3 a	11.0 ± 1.9 b
perp	2.0 ± 0.6	5.2 ± 1.5			5.0 ± 1.3	7.4 ± 1.1
Root angle						
horizontal (0-30°)	3.9 ± 1.3	7.7 ± 2.1			6.8 ± 2.2 a	15.6 ± 2.8 b
oblique (30-60°)	1.9 ± 0.7	3.1 ± 0.6			4.4 ± 0.9	3.9 ± 1.1
vertical (60-90°)	2.4 ± 0.4 a	7.0 ± 1.1			9.7 ± 2.6	7.2 ± 1.8

Table 4

Mean value ± s. e. of measured architectural traits depending on the mode of root failure for the three species. Values with different letters are significantly different at $p<0.05$.

Architectural traits	Species and mode of failure					
	J. curcas (n=9)		*R. chinensis* (n=6)		*R. communis* (n=9)	
	broken roots	slipped roots	broken roots	slipped roots	broken roots	slipped roots
Mdiam (mm)	0.51 ± 0.05 a	0.39 ± 0.04 b	0.22 ± 0.03	0.23 ± 0.03	0.57 ± 0.02	0.47 ± 0.02
L_{sup} (mm)	222.4 ± 25.2 a	143 ± 14.9 b			297.9 ± 31.2 a	186.0 ± 17.0 b
BD_{sup} (Nb.m-1)	20.8 ± 3.4 a	55.0 ± 6.3 b			133.9 ± 9.8 a	352.9 ± 35.3 b

Fig. 1

a) Stress-strain curve of a shear test. τ: tangential stress, ε: tangential strain, A: peak-type curve, B: plateau-type curve, y: yield point, G: shear modulus, res.: residual deformation, J: energy of deformation; b) Mohr-Coulomb criterion of failure. τ_{yield}: tangential stress at yield point, σ_n: normal stress at yield point, ($\sigma_{n,i}$; τ_i): normal and tangential stress at yield point for shear test i, *c'*: effective cohesion of the material, Φ': effective internal friction angle of the material.

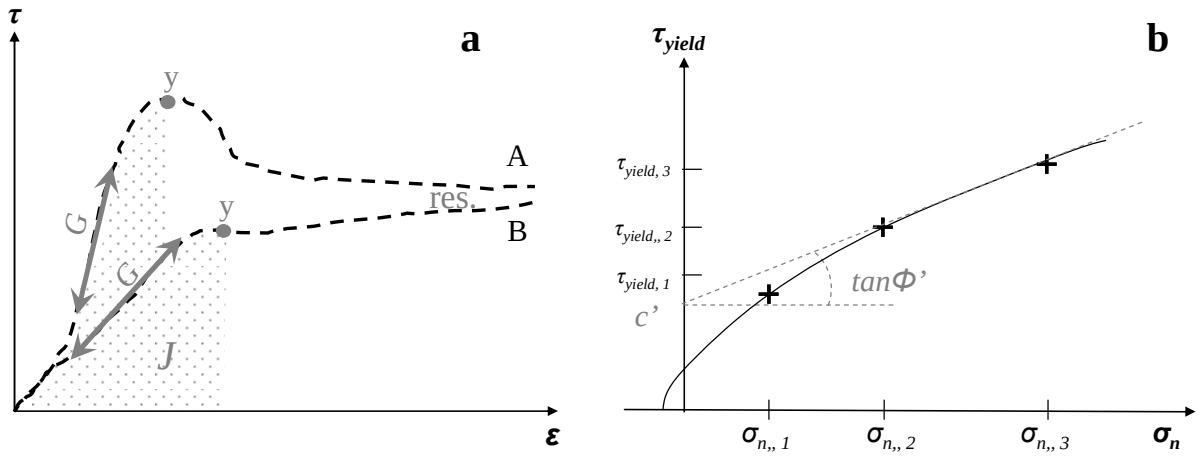
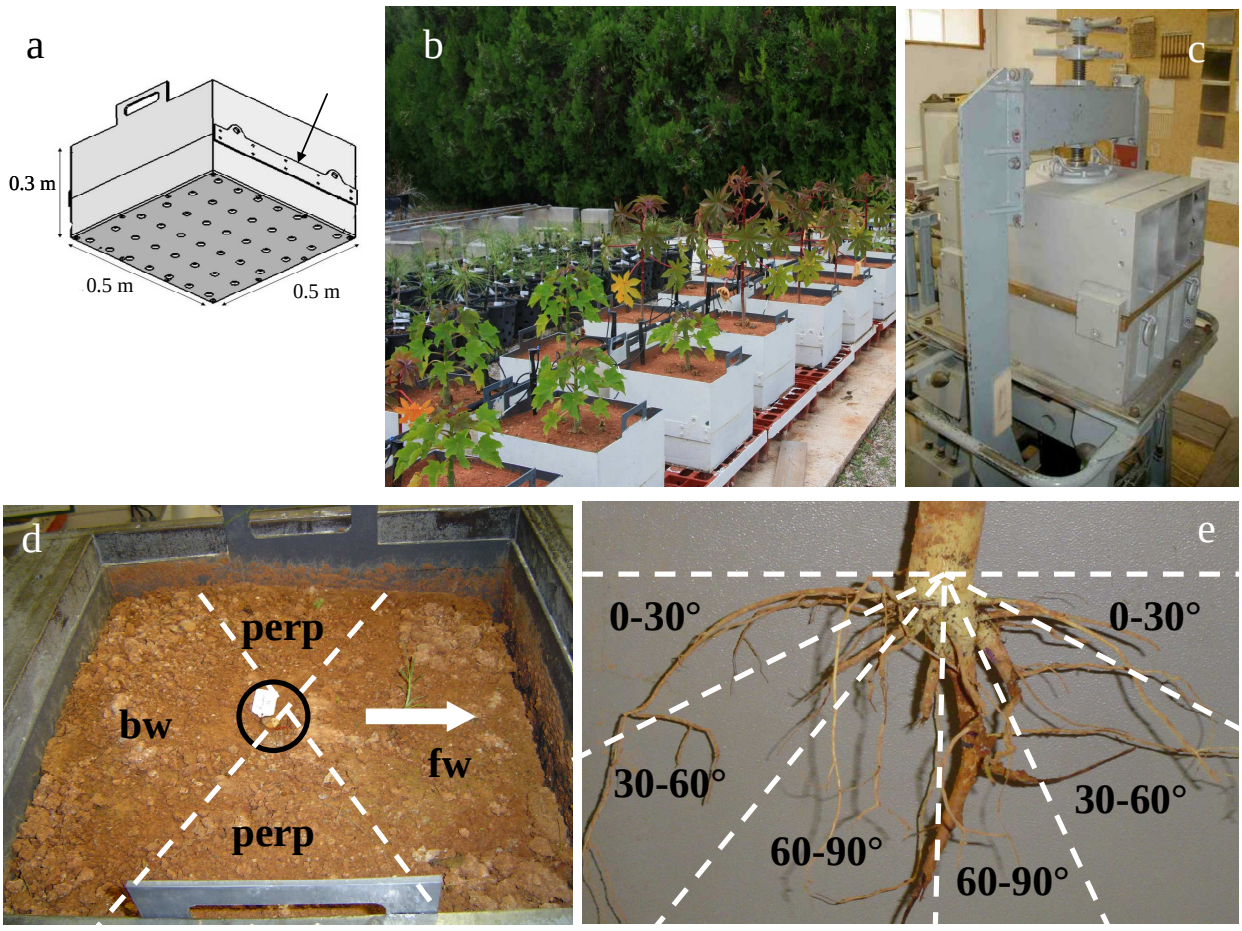


Fig. 2

(a) The PVC shear box was composed of two parts which could slide over each other during testing. These two parts were attached with a PVC plate (arrow) during plant growth. Holes drilled underneath the box allowed water to drain freely. b) Plants at the nursery (*J. curcas* in foreground and *R. communis* in background). c) Casagrande direct shear apparatus. d) The four sectors defining root azimuth classes: fw: roots growing in the direction of shear, bw: roots growing away from the direction of shear and perp: perpendicular to the shearing direction (white plain arrow). The black circle shows the position of the plant collar. e) The six sectors defining the three root angle classes: 0° to 30° (horizontal roots), 30° to 60° (oblique roots) and 60° to 90° (vertical roots).



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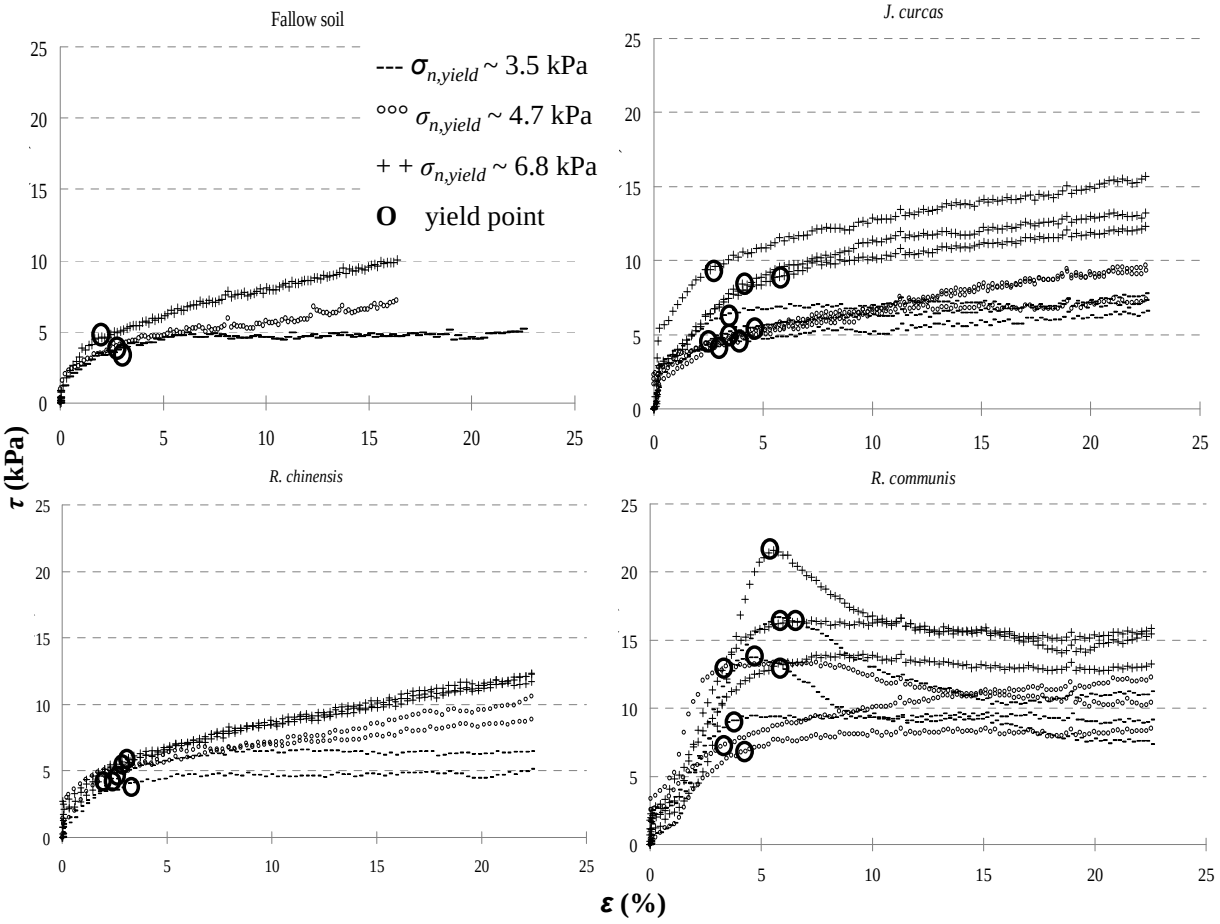
829 Fig. 3

830 Stress-strain curves obtained for fallow soil and the rooted soil blocks for each species

831



832 Fig. 4

833 Mechanical properties per confining pressure (σ_n) and species. a) Stress at yield point (τ_{yield}); b)

834 Strain at yield point (ε_{yield}); c) Shear modulus (G); d) Residual stress (τ_{res}); and e) Total energy

835 of deformation (J)

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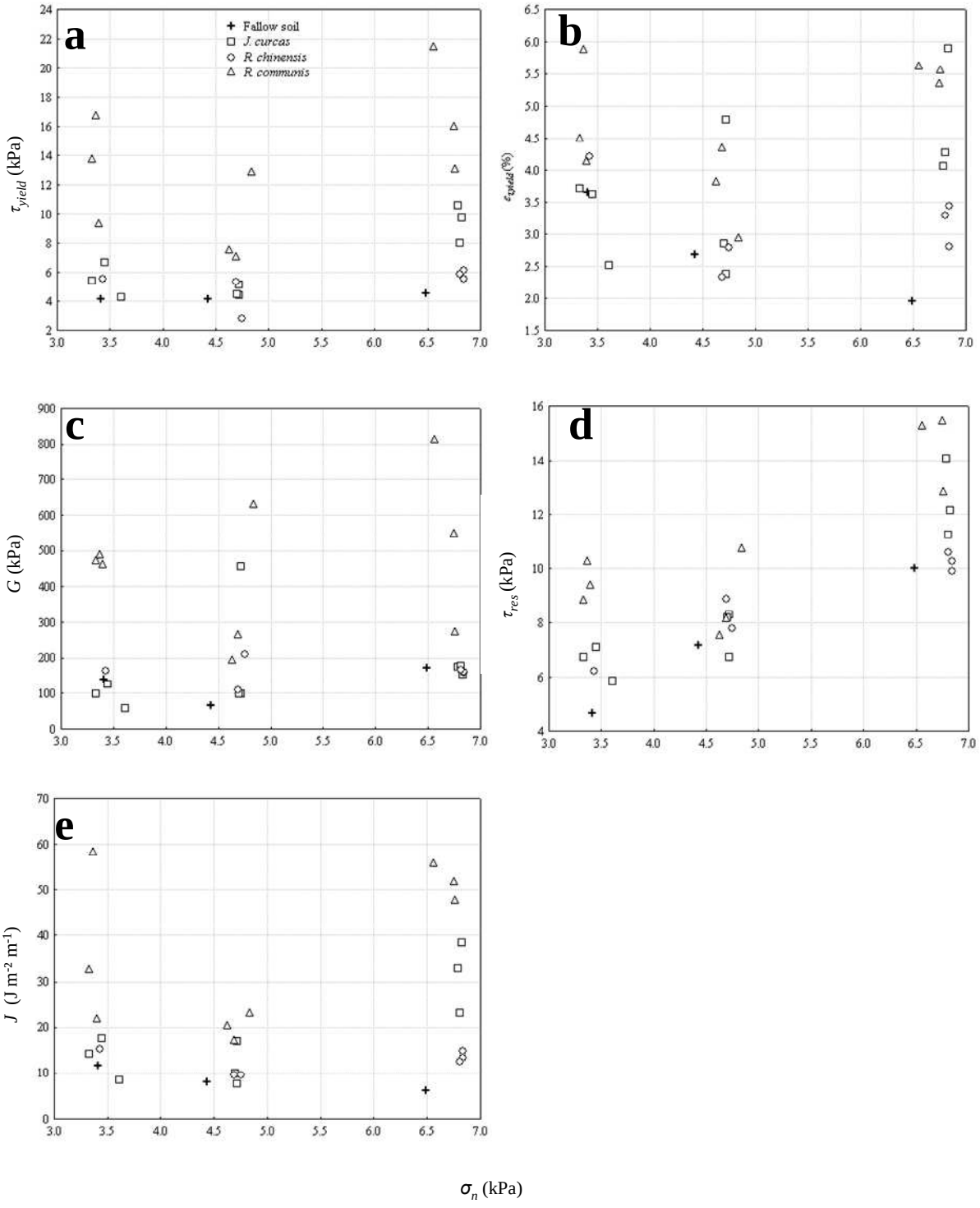

837 Fig. 5

838 a) Projection of the measured architectural traits on the plane represented by the first two

839 factors; b) Projection of plant individuals on the plane comprised by the two first factors

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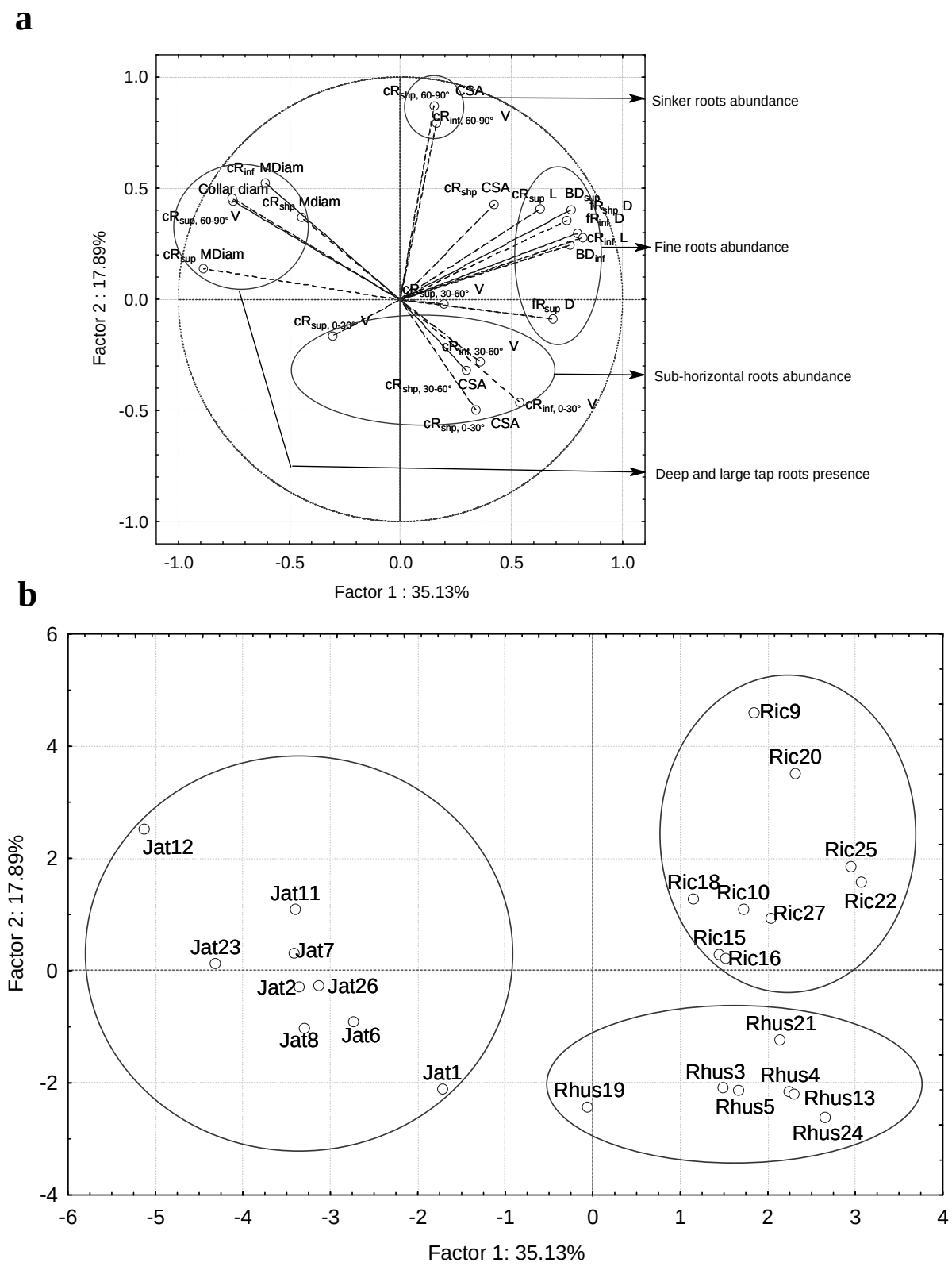
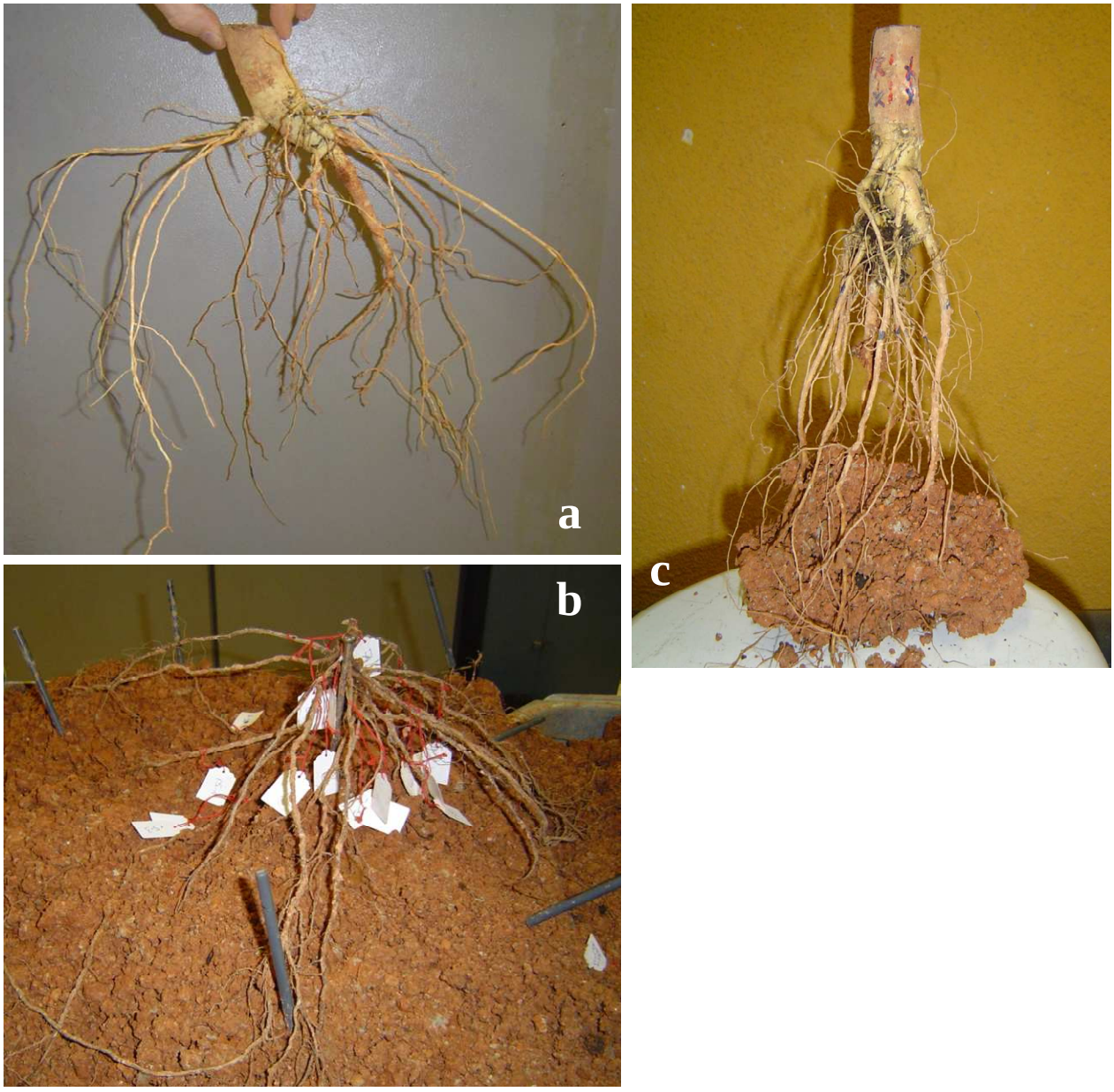


841 Fig. 6

842 Root systems of the three tested species. a) *J. curcas* possessed a large stem-root base from
843 which a few large and deep taproots emerge. Sinker and lateral coarse roots were few, and
844 fine roots were not abundant; b) *R. chinensis* had a thin stem-root base and long horizontal
845 branched roots with many fine roots; c) *R. communis* had a large stem-root base which
846 tapered rapidly and from which several highly branched long sinkers emerged. Fine roots
847 were also numerous.

848



Chapitre I

Partie I. 2.

► Ghestem, Sidle, Stokes. 2011. The influence of plant root systems on subsurface flow: Implications for slope stability. BioScience 61: 869-879. doi: 10.1525/bio.2011.61.11.6.

The Influence of Plant Root Systems on Subsurface Flow: Implications for Slope Stability

MURIELLE GHESTEM, ROY C. SIDLE, AND ALEXIA STOKES

Although research has explained how plant roots mechanically stabilize soils, in this article we explore how root systems create networks of preferential flow and thus influence water pressures in soils to trigger landslides. Root systems may alter subsurface flow: Hydrological mechanisms that promote lower pore-water pressures in soils are beneficial to slope stability, whereas those increasing pore pressure are adverse. Preferential flow of water occurs in the following types of root channels: (a) channels formed by dead or decaying roots, (b) channels formed by decayed roots that are newly occupied by living roots, and (c) channels formed around live roots. The architectural analysis of root systems improves our understanding of how roots grow initially, develop, die, and interconnect. Conceptual examples and case studies are presented to illustrate how root architecture and diverse traits (e.g., diameter, length, orientation, topology, sinuosity, decay rate) affect the creation of root channels and thus affect preferential flow.

Keywords: macropores, root channels, preferential flow paths, landslides, root architecture

A *landslide* is defined as the gravitational movement of a mass of soil or debris along a sliding surface at depth (Sidle and Ochiai 2006). It is well known that vegetation can play a major role in slope stability through hydrological and mechanical processes; these effects can be adverse or beneficial to stability (table 1). Hydrological mechanisms that lead to lower pore-water pressures in the soil are beneficial, whereas those that increase pore pressure are adverse. Of the mechanical mechanisms, those that increase shear resistance in the slope are beneficial, whereas those that increase shear stress are adverse (Greenway 1987). Mechanical and hydrological processes have usually been studied separately, but they strongly interact and can even offset one another. Therefore, the two processes need to be considered together when assessing the stabilization of hillslopes by vegetation.

Canopy interception of precipitation—both rain and snow—and subsequent evaporation can prevent considerable amounts of water from reaching the soil surface and may mitigate landslide occurrence. However, surface soil acts as a more significant buffer and tends to dampen pore pressure propagation, and the effect of surface soil probably exceeds most canopy effects during the redistribution of heavy rainfall (Keim and Skaugset 2003). The role of roots in extracting soil water by evapotranspiration is rather limited during cold, wet seasons, when landslides typically occur in temperate regions, whereas in tropical and semitropical climates, such evapotranspiration benefits may be more substantial (Simon and Collison 2002, Sidle et al. 2006).

To reduce subsurface pore-water pressure, efficient subsurface drainage is necessary. Plant roots, alive or dead, can promote slope drainage by functioning as hillslope-scale preferential flow paths that drain subsurface water away from potentially unstable sites. Conversely, when root channels converge or when subsurface flow abruptly terminates in the slope (e.g., dead-end channels), water pressure may concentrate in critical zones in the slope, thus promoting instability. Therefore, flow paths may result in both positive and negative consequences on slope stability. We attempt to answer the question of what the mechanisms and configurations are in which a root or an assemblage of roots plays a positive or a negative role in slope stability. To address this question, precise knowledge of the disposition of roots within the slope is needed, and we suggest that the methodology proposed for root architecture analysis is a suitable approach. First, we describe how roots can actually provide preferential flow paths, then we articulate how root-system architecture can affect preferential flow and improve our insights into slope failure. Finally, implications of vegetation cover for slope stabilization are illustrated by case studies.

How roots create a stable channel when growing in the soil

Water flows through two domains in soil: the soil matrix, consisting of both uniform saturated and unsaturated flow through fine pores, and preferential flow pathways, consisting of single or interconnected macropores (figure 1a).

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Table 1. Hydrological and mechanical mechanisms affecting slope stability and their influence on shallow and deep-seated landslides.

Mechanisms affecting slope stability	Type of landslide influenced by the mechanism: Shallow, rapid landslides	Deep-seated landslides
Hydrological mechanisms		
Interception of rainfall by canopies	mB	mB
Organic litter increases ground surface roughness and "Biomat flow" (Sidle et al. 2007)	mA (B for runoff)	mA
Roots act as preferential flow paths	B or A	B or A
Roots extract water from the soil	B or mA	B or mA
Mechanical mechanisms		
Roots act as reinforcement fibers in the soil matrix	B	B
Strong roots tie across planes of weakness and anchor soils into the more stable substrate	B	mB
The weight of trees increases the normal and slope-parallel force components	mB or mA	mB or mA
Wind transmits dynamic forces to the soil mantle	mA	mA

A, adverse influence; B, beneficial influence; m, marginal influence.
Source: Adapted from Greenway (1987) and Sidle and Ochiai (2006).

Because of the lack of a consensus definition, we consider *macropores* to be all types of pores with a diameter of more than two millimeters (mm) that support both uniform and nonuniform flow. Various studies have reported macropore diameters ranging from 30 micrometers (Marshall 1959) to many centimeters (Pierson 1983). One way to classify macropores is to distinguish between biotic and nonbiotic macropores. Biotic macropores include root channels and animal burrows, whereas nonbiotic macropores are formed by freeze–thaw and wetting–drying cycles, the dissolution of soil materials, natural soil aggregation, and subsurface erosion (Aubertin 1971). In this article, we deal with biotic macropores and, more specifically, with root channels.

Roots are usually classified as either coarse or fine, with a diameter of 2 mm typically used as the threshold between the two groups (Stokes et al. 2009). In other studies, different criteria have been used to distinguish between coarse and fine roots, such as the ability of fine roots to absorb water and nutrients, whereas coarse roots are more rigid, anchor the plant to the soil, and provide the structural skeleton that supports the fine roots (Zobel 2005).

Initially, fine roots grow in length; this stage is the primary growth stage, which consists of organogenesis and organ length extension. During primary growth, the root apex increases temporarily in diameter (figure 2a) to facilitate penetration through soil material (Bengough et al. 1997). During this process, soil particles may reorganize around the apex surface (figure 2b). Around the thinner portion of the root that follows the apex, where root hairs appear, soil particles amalgamate with sloughed cells that emanate from the cap of the root apex and with the mucilages emitted by both the root and microorganisms surrounding the root to create the *rhizosheath* (figure 2c). This rhizosheath can be rather large up to 2.5 to 3.0 times the volume of subtending root in monocotyledon root systems—or can even be absent in dicotyledonous root systems (McCully 1995). Because the rhizosheath adheres to the root in dry conditions, this tight mantle around the roots is not the entity that will create a structured channel for preferential flow. The *rhizosphere* is defined as the ensemble composed of the roots, the rhizosheath if there is one, microorganisms, and the soil around the roots (Tarafdar and Jungk 1987), not including bulk soil. The rhizosphere is a focal point in many studies because of its complexity; it exhibits physical, chemical, and biological characteristics that differ from those of rootless soil. The rhizosphere can extend several millimeters beyond the root. For

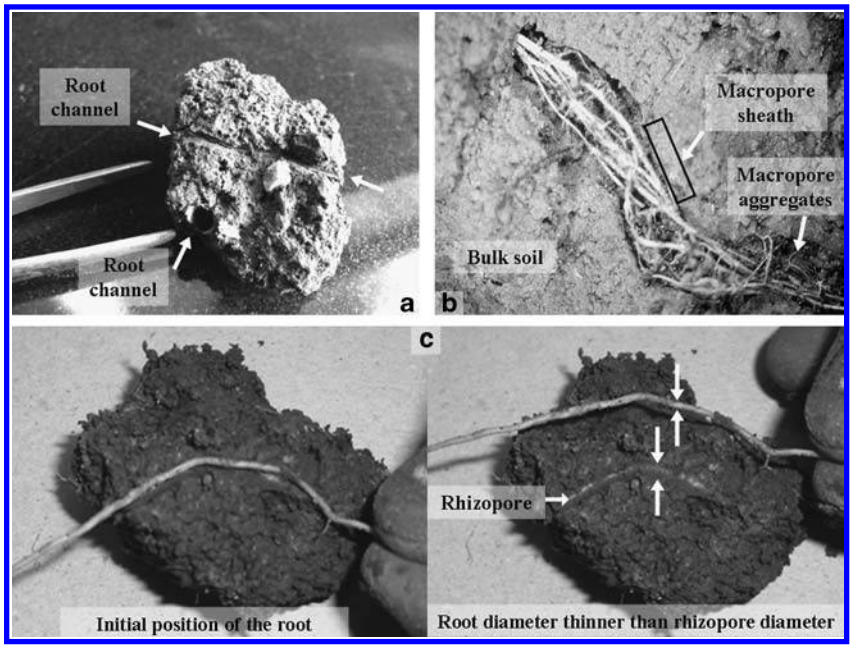

Figure 1. Illustrations of different types of root channels. (a) Two macropores (empty root channels) in silty-textured loam from the Yunnan province, China. (b)* Brassica napus *roots growing in an existing root channel or biopore. Photograph: Clive E. Pankhurst, Commonwealth Scientific and Industrial Research Organisation Land and Water. (c) The root diameter can be thinner than the rhizopore diameter, leaving a ring-shaped space for potential water flow.

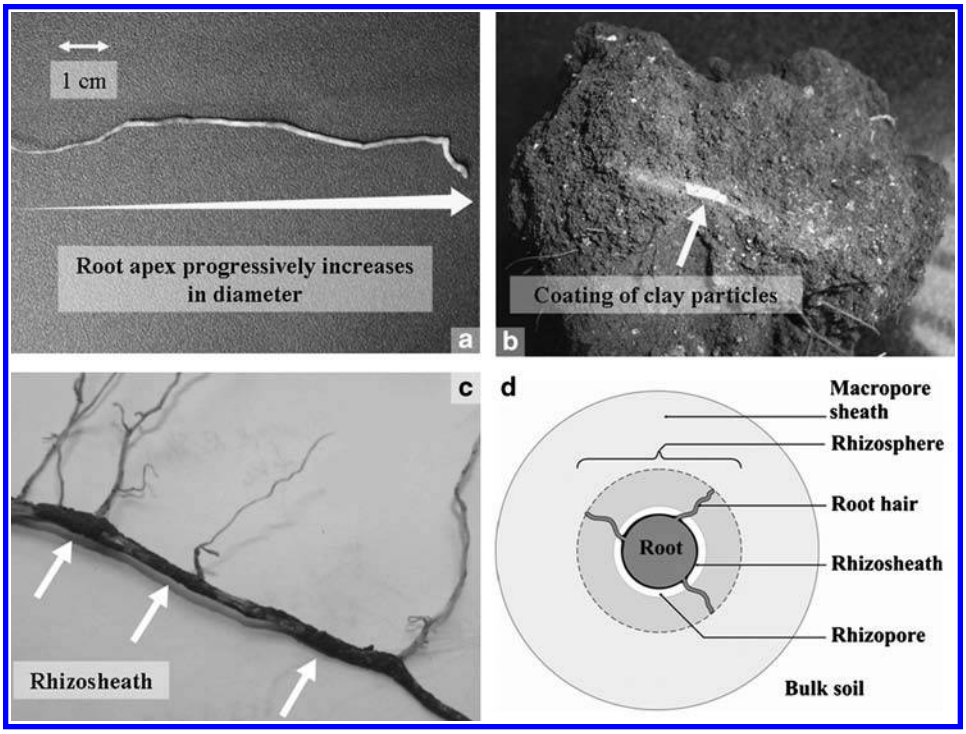

Figure 2. Mechanisms by which fine roots create a stable channel when growing in the soil. (a) As fine roots grow in length, their apex may increase in size to facilitate penetration through soil material. (b) During root penetration, soil particles may reorganize around the root surface, as is shown by this coating of clay particles on the sides of the channel. (c) Behind the root apex, soil particles amalgamate with sloughed cells and mucilages to create the rhizosheath, shown here (white arrows) in an* Agave americana *root. (d) Structure of a macropore, including the rhizosheath, rhizosphere, rhizopore, and pore sheath. Abbreviation: cm, centimeters.

example, soil microorganisms associated with the presence of roots and the enzymes these microorganisms produce can be active within a 4-mm radius around the root (Fageria and Stone 2006). The rhizosphere increases organic matter content around the root, which supports soil aggregation (Fageria and Stone 2006). Fungal mycelia improve the stability of soil aggregates by growing around soil particles and amalgamating them, which increases mechanical stabilization. An increase in aggregate stability will improve channel longevity. Glue-like polysaccharides, which are products of fungal metabolism, also cement soil particles together, which improves chemical stabilization (Tisdall and Oades 1982). Roots themselves release large amounts of organic materials into the soil as the rhizosheath decays and is replaced. Mucilages from roots and microorganisms have the capacity to stabilize soil structure in the rhizosphere by increasing the strength of the bonds among particles.

Mucilages that clog soil aggregates physically decrease the wetting rate, and fungi in the rhizosphere are known to chemically induce water repellency (Hallett et al. 2006). Organic compounds released by roots and microorganisms are hydrophobic below a certain threshold of moisture, but when soils are wet, as is the case when landslides are triggered by rainfall, these organic compounds are highly hydrophilic (Dekker et al. 1998). Coarse roots do not generally emit exudates, but physical effects may occur that expand the diameter of the root channel through the accumulation of woody tissues, which induces compression forces and rearranges mineral and organic soil particles along the surface of the root (Blevins 1968, Aubertin 1971). The chemical and biological activity in the rhizosphere, together with the physical action of the root, helps establish a relatively stable channel, which could be called a *rhizopore*.

Growing roots may develop inside preexisting pores (figure 1b). For example, in an untilled field of wheat (*Triticum aestivum* L. cv. Janz) that had previously been planted with alfalfa (*Medicago sativa*), 20% (near the surface) to 90% (at depth) of roots grew inside existing pores of clay loam soil (White and Kirkegaard 2010). In some cases, void space may still occupy up to 40% of the macropore volume, even if the roots tend to stick to the macropore wall along portions of the circumference (Kooistra et al. 1992). In other cases, roots cluster inside a former macropore until up to 10 roots are compressed together (White and Kirkegaard 2010). Even more roots were found in and around macropores than would be expected if their placement were random, which indicates a preferential association between roots and macropores (Stewart et al. 1999). The zone surrounding the rhizosphere, with a higher concentration of roots and a higher microbial biomass density than both the rhizosphere and bulk soil, is called the *macropore sheath* or the *macrosheath* (Pierret et al. 1999; see figure 2d for a summary of terms used in this article). This preferential concentration of roots inside existing macropores and macrosheaths may be due to the easier access to air and water rather than to the low mechanical resistance of these zones. The effects of low mechanical resistance may be beneficial for some species, for which root penetration is retarded in fine-textured soils because of the presence of clay, which acts as a cementing agent. For these species, root growth in or in association with former macropores is more common. Root growth into macropores may also be more common in massive-structured soils (i.e., soils with high bulk density), in which

root penetration is less than that in lower-bulk-density soils. Even if a root is larger in diameter than the channel it encounters, it will be able to enter if the channel walls are weak (Kar and Ghildyal 1975). Roots that grow within the macropore sheath benefit from low soil mechanical resistance and proximity to water, air, and nutrients, but do not experience the drawbacks of growing inside the macropore because the sheath provides greater root–soil contact than the interior of the macropore. Nevertheless, root growth inside the macropore and in the sheath presents other difficulties: (a) Root uptake of low-mobility nutrients (e.g., phosphorus) is restricted because the former root may have previously consumed these nutrients, (b) root clusters can lead to drier soil zones, (c) development of pathogenic fungi is more common, and (d) foraging or grazing soil fauna may be more abundant (Pierret et al. 1999).

In summary, three categories of root channels coexist: channels occupied by the root that made it, empty or nearly empty channels occupied by a decaying root, and channels that were previously empty but that are newly occupied by roots.

How root channels contribute to preferential flow

Although few data exist concerning how root channels contribute to preferential flow, we can induce the likely mechanisms that facilitate such flow paths from root-architecture data and our knowledge of subsurface flow processes. In this article, we use the term *preferential flow pathways* to distinguish those root channels from other pathways that actively transmit water. As was already stated at the beginning of this article, soil wetness depends on infiltration and subsurface flow processes. Water can directly enter macropores that are open to the soil surface. Water moves through soils on the basis of an energy gradient—from high to low energy. Therefore, water does not necessarily flow from higher to lower elevations, although this is generally the case. For water to enter a subsurface macropore and initiate preferential flow, either the entire perimeter or a portion of the macropore should be saturated (or nearly saturated). Therefore, macropores located below a water table or within a limited zone of saturation capture subsurface water and initiate a preferential flow. In contrast, macropores located in unsaturated areas and those surrounded by hydrophobic conditions are bypassed, which causes water to flow around these voids. The network of interconnected macropores is not obvious and continuously evolves—if not physically, at least in its flow activity (Nieber and Sidle 2010).

Numerous investigators have noted water discharging from visible decayed root channels, but water has also been observed to flow from channels occupied by live roots (Aubertin 1971, Noguchi et al. 1997a, Newman et al. 2004). As such, all types of channels associated with roots can act as preferential flow paths and can interact to create networks that potentially include entire hillslopes (Sidle et al. 2001).

The proportion of the total macropore population represented by both live- and dead-root channels is significant, sometimes up to 70% (Noguchi et al. 1997b) or even up to 100% (Newman et al. 2004) of the macropore population in the upper organic-rich soil layers and up to 35% of the total soil volume (Aubertin 1971). Because the estimated volume of root channels is always greater than the potential volume of water discharged from these channels, it is clear that not all root channels support water drainage (Li and Ghodrati 1994). To our knowledge, no study has segregated live- from dead-root channels with the aim of better understanding preferential flow processes and function.

The root—and its rhizosheath if it has one—evolves within the rhizopore, thereby leaving a ring-shaped or semi-ring-shaped space for potential water flow in response to diameter changes (figure 1c). Fine-root diameter can decrease up to 60% within a diurnal cycle of desiccation at peak afternoon radiation, followed by overnight rehydration (Huck et al. 1970). Roots also retract in volume during dry seasons (Nobel and Cui 1992). Spaces between living roots and their channels can be created near the trunk when windy conditions prevail and the stem bends during wind gusts, which cause the roots to move and displace soil around the channel walls (Hintikka 1972). Such windy conditions principally act on coarse and rigid roots and often precede or accompany rainstorms; therefore, in addition to wind stress (table 1), they can initiate preferential flow along roots starting from the ground surface and may contribute to landslide initiation. Another mechanical effect that can create preferential flow around roots is the tension exerted during minor soil slippage. Such tensile forces may decrease root diameter and might remove part of the bark. This process may cause the root channel to collapse, or it may result in the development of an empty space around the root that allows water to rapidly infiltrate, which causes pore-water pressure to increase in an already mechanically weakened zone. It can be supposed that a series of such microfailures can in turn trigger a larger landslide (Chigira 2001).

The space between the root and the soil can be detrimental to plant fitness, because the root's uptake of water and nutrients may be limited, or it can be beneficial, as in very dry conditions in which the air occupying the space acts as a buffer and prevents the soil from extracting water from the root. Van Noordwijk and colleagues (1992) showed that root hairs are more numerous when spaces exist between the root and the soil. Root hairs may not be tightly bound to the soil because they do not penetrate the bulk soil (Kooistra et al. 1992) and because they do not increase root anchorage (Bailey et al. 2002).

Research on channels occupied by decaying roots relies on a better understanding of root necrosis and root longevity. Studies in which minirhizotrons (microvideo cameras) were used to monitor growth and in which isotope-based estimates of carbon residence times in fine roots were used showed that the life spans of various roots can vary from several days to five or six years (Strand et al. 2008). Assessing root decay and regrowth is difficult because turnover depends on many parameters, such as the plant species, root

thickness, age, and environment. The decay and regrowth rates have often been modeled as time-dependant functions (Burroughs and Thomas 1977) correlated with plant species, root densities in the soil, and, at the root scale, with the functional category of the root (Atger and Edelin 1994). Root resistance to decay was also found to be higher in resinous roots than in nonresinous roots (Ziemer and Swanston 1977). Therefore, preferential flow networks will develop more slowly after the death of members of a species that have a high resin content in their roots (e.g., conifers). At the onset of senescence, the root channel is filled with organic material derived from the root itself. Depending on the species, the type of root, and the climate, the bark can disappear first or can remain and contribute to the integrity of the channel. If the rhizopore remains empty, clay particles may first deposit as skins on the sides of the channel (figure 1b; Aubertin 1971). With time, other particles crumble into the channel if they are eroded from the interior through sapping caused by erosion and abrasion during subsurface sediment transport. Thus, seepage forces enlarge the channel but may eventually obstruct it. Roots that occupy an old rhizopore can be initiated by the mother root system or by neighboring root systems. These dead-root channels thus provide interconnections among root systems.

Therefore, to understand how preferential flow develops and evolves with time, it is important to evaluate root emission (i.e., the birth of new roots) and root decay, not only in a quantitative way—by specifying decay and emission rates—but also in terms of location, the angle of insertion, and the rate of growth within a single root system.

Root architecture as an approach to understanding preferential flow

As far back as the eighteenth century, when scientists and naturalists began looking at the morphological characteristics of plants, they noticed that some of these features were inherent to a given species and could therefore be useful in the process of classifying species. It was not until the 1970s that the study of plant architecture was formalized, with rules to describe the equilibrium between endogenous growth processes and the exogenous constraints exerted by the environment on plant development at any given time (Hallé and Oldeman 1970). The aim of architectural analysis is to identify and understand these endogenous processes and to separate them from the plasticity of their expression that results from external influences. Architectural analysis is thus a tool to describe the progressive development, or *ontogeny*, of a given species. This type of analysis takes into account that a plant is a modular organism composed of several units. Recently, more emphasis has been placed on the implications of plant architectural analysis for agriculture and crop yield improvement, as well as on commercial forestry and the urban planning associated with tree growth and health (Barthélémy and Caraglio 2007).

Roots provide a weak visual component of plant architecture because of the difficulties in observing them and their indistinct morphological characteristics. On the basis of crude observations of the overall shape of root systems or of simple morphological classifications such as "lateral" or "vertical" roots, the conceptualization of architectural models for different root systems has been difficult. In more recent studies, the ontogeny of root systems has been investigated. For example, Atger and Edelin (1994) described successive architectural patterns at different physiological stages of root-system formation. Khuder and colleagues (2007) demonstrated the reiteration of architectural patterns within root systems. Functional properties have been used to define different categories of roots. This approach first used the term *root functional architecture* (Zobel 2005). For example, the ability to uptake water and nutrients varies from one root to another and even along individual roots. A root with a high specific root length to root mass density (SRL:RMD) ratio would be better equipped to scavenge nutrients in the soil, whereas a low SRL:RMD ratio would characterize a root in which the plant invests more resources for mechanical support (Roumet et al. 2006). To better describe root functional architecture, topological analysis (Fitter 1985) can be used to quantify branching patterns (i.e., how roots are geometrically linked). The potential effects of different branching patterns on slope stability were summarized by Stokes and colleagues (2009). The architectural analytical methods to be used must be chosen carefully, in accordance with the traits to be quantified (Danjon and Reubens 2007). Excavation of the entire root system, root counts on profile walls, measurements of windthrown trees, and soil coring can provide data to support empirical and numerical modeling. Predictive models are also useful for estimating root densities and predicting root growth (Pierret et al. 2007) without time-consuming excavation.

How different root architectures can influence preferential flow paths

The architectural analysis of plant root systems growing on hillslopes can help us understand the role that roots play in preferential flow. Root traits (e.g., diameter, length, sinuosity, decay rate, orientation, topology) partially determine root-channel development and thus have an impact on preferential flow. In general, longer and wider root channels more efficiently route water away from unstable zones; however, some root orientations may be more efficient than others. Roots oriented downslope convey water more efficiently (figure 3a). Depending on their orientation, large root extremities can represent dead-end paths for water flow, thus leading to a local increase in water pressure (figure 3b). The collapse of root channels acts in a similar manner.

Depending on their orientation and position with regard to the stem, forks may divide or concentrate flow. Zones of water concentration where root forks converge downslope may increase water pressure (figure 3c). Forks can also occur as the result of interconnections among roots from different plants.

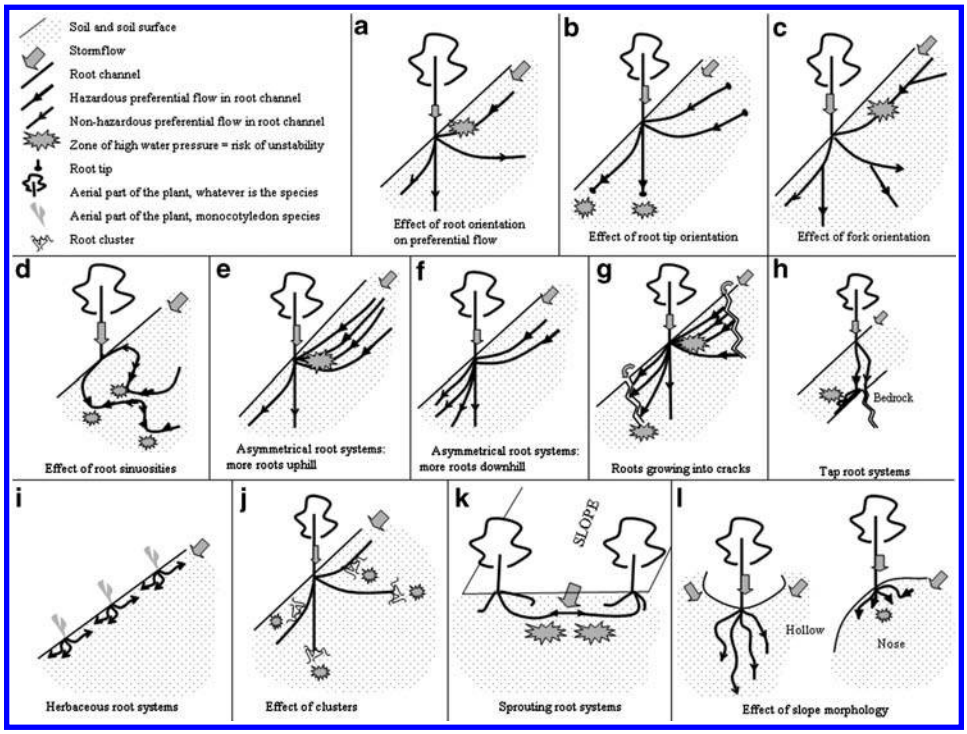

Figure 3. Illustrations of different scenarios of the effects of root architecture on preferential flow. (a) Downslope root orientation is more efficient for transporting excess water. (b) Root extremities can represent dead-end paths for water flow. (c) Root branching may divide or concentrate flow. (d) Sinuous roots divert or concentrate water fluxes, depending on their orientation. (e) When the majority of roots grow upslope, there is a potential for pore-water accretion at shallow depths to occur near the plant stem. (f) When more roots grow downslope, drainage of water is facilitated. (g) Roots growing toward cracks enhance the risk of water accretion. (h) Taproot systems convey water to deeper soil, where it can drain into cracks in the bedrock if cracks are present. However, if the soil–bedrock limit is impermeable, zones of high water pressures can be created. (i) Tuft-root systems allow water to infiltrate into upper soil layers. (j) Clusters of roots act as sponge-like structures and concentrate high water pressures. (k) Roots oriented perpendicular to the slope gradient capture downward water flow. (l) Topographic situations can combine various water-flow and root-distribution patterns.

Sinuous roots are variants of forks: Depending on their orientation and location, they may either divert or concentrate water fluxes. In situations in which root curvature concentrates fluxes, high pore-water pressure can induce unstable zones in the soil (figure 3d).

Root systems that exhibit preferential growth upslope or downslope need special consideration. From a strictly mechanical point of view, the orientation in which roots are aligned with regard to slope direction can affect soil reinforcement, depending on whether the plant is located at the top or at the bottom of a slope (Genet et al. 2010, Thomas and Pollen-Bankead 2010). From a hydrological perspective, root orientation is also important. In some systems, more roots are oriented downslope than upslope (Stokes et al. 2009). This preferential gravitropism depends on the species, on nutrients, and on the soil's physical properties. If there are more roots growing downslope, drainage of water is facilitated in this direction (figure 3f). That some systems have more roots growing upslope from the stem suggests that some roots may undergo hydrotropism rather than gravitropism if more water is located upslope. Roots do not search for water actively but are able to reorient or branch when they reach a moist patch. Systems with more roots growing upslope will drain water less efficiently and will promote pore-water accretion at shallow depths near the main stem (figure 3e).

Depending on the climate, dry seasons can correspond to hot or cold temperatures. In the former case (i.e., dry, hot conditions), cracks in the soil can appear, caused by the swelling and shrinkage of clay minerals. In colder conditions, cracks occur because of the freeze–thaw process. Roots can proliferate in cracks that regularly accumulate water during even short rainfall. During heavy rain, water flow in cracks increases, and roots may even become asphyxiated and die. The growth characteristics of roots in soil cracks can therefore have consequences for the stability of slopes (figure 3g).

Structural cracks also exist in bedrock. If roots grow through the soil and are able to penetrate the bedrock and fissures in the bedrock, the water they convey may dissipate inside the bedrock. Such a pathway may reduce pore-water pressure accretion in the soil but could transfer such pore pressures into the bedrock and contribute to rockfall. In contrast, if roots do not grow into the bedrock, a layer of high root density may develop above the bedrock, which may induce locally high pore pressures and which could trigger landslides along this potential slip surface (figure 3h). Many inherently deep-rooting species can be found in thin soils over bedrock (Stokes et al. 2009). Deep-rooting species can benefit from preferential flow, because flow may short-circuit the upper soil layers. Therefore, deep-rooted coppiced plants, with their root systems already in place, can grow more rapidly and more vigorously than newly planted individuals, even when the latter are fertilized.

The effects of tuft root systems, which are typical of herb species, on water pathways are unclear. Inhibiting or diffusing water flow at depth near potential slip surfaces will help promote the stability of slopes. However, in reality, the soil surface is not homogeneous, and a single crack can concentrate subsurface flow. Therefore, fibrous (figure 4a) and shallow root systems dispersed along the slope may act as preferential flow paths that dissipate pore-water pressure at a given point (see the upslope portion of figure 3i).

Clusters of fine roots are sometimes observed along or at the end of coarse roots and correspond to zones of major nutrient and water uptake. Fine roots have high decay and emission rates, and clusters may therefore manifest as sponge-like structures. These structures may soak up water during heavy rains and may contribute to high-water-pressure nodes, especially at dead-end flow paths (figure 3j).

In certain species, superficial underground creeping stems (rhizomes) or roots ensure asexual reproduction. These organs link two or more aboveground vegetative structures together. If they are oriented perpendicular to the slope, such structures may intercept downslope water flow, which could lead to a local increase in water pressure at the zone of interception, which, in turn, could result in a locally fragile zone on the slope (figure 3k). As the plant community matures, these structures may well develop into a dense root mat.

Topography is also important with regard to subsurface water movement and slope stability. Concave slope segments (hollows) promote the convergence of subsurface flow (Tsukamoto 1987). However, some studies indicate that roots in hollows are more evenly distributed in the soil column than those on convex slopes where roots concentrate on the upper horizons of soil (Hales et al. 2009). Therefore, in hollows, water flows may be diverted more efficiently toward deeper soil (figure 3l). As such, root architecture, along with its interaction with water, nutrients, and topography, can affect slope stability.

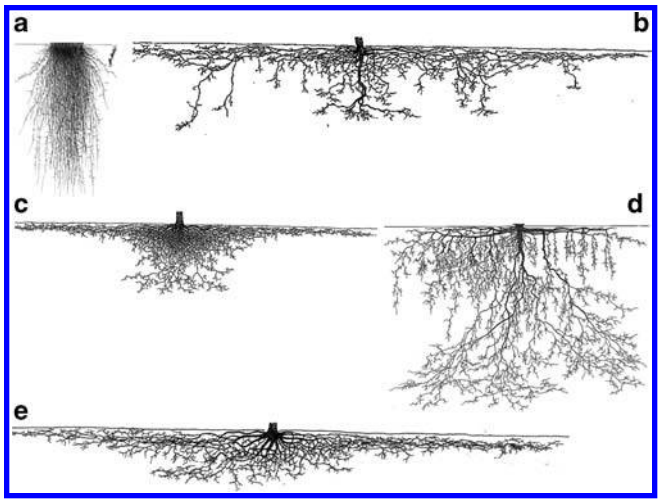

Figure 4. Five basic types of root systems. (a) Tuft root systems typical of Poaceae. (b) Taproot system. (c) Heart-shaped root system. (d) Root system with a large taproot and large horizontal lateral roots from which emerge vertical sinkers. (e) Plate-shaped root system. Sources: Panels (a) and (d) are reprinted from Kutschera and Sobotik (1997) with permission from Landesmuseum. Panels (b), (c), and (e) are reprinted from Kutschera and Lichtenegger (2002) with permission from Stocker.

Case studies of how root-system architecture influences subsurface flow

Examples in which the interactions among root architecture, preferential flow, and landslides have been examined are few. One of the earliest studies was by Gaiser (1952), who hypothesized that root channels must serve as large openings for rapid water flow. He therefore mapped the presence of cone-shaped channels formed from decayed roots through the A, B, and C horizons of a temperate forest soil. The forest was dominated by white oak (*Quercus alba*), with black walnut (*Juglans nigra*), hickory (*Carya* spp.), and dogwood (*Cornus* sp.) present in smaller quantities. The shrubby dogwood possesses a highly branched superficial root system, whereas the three tree species generally have much deeper root systems (Kutschera and Lichtenegger 2002). In particular, white oaks usually possess a taproot system when they are young, with a single large, vertical central root and thinner, less numerous lateral and sinker roots (figure 4b). But when white oaks mature, their taproot growth decreases, and the proportion of lateral, oblique, and sinker roots increase, forming a heart-shaped root architecture (figure 4c; Köstler et al. 1968). Except for one 90-year-old tree, the white oaks examined by Gaiser (1952) were less than 20 years old. Therefore, the cone-shaped vertical channels, which decreased from 36 to 5 centimeters (cm) in diameter at the soil surface to 3 to 0 cm in diameter at the furthest extremity, were likely formed by the taproots of juvenile white oaks and allowed for an increased infiltration of water to deeper soil (figure 3h). Gaiser (1952) concluded that further research on subsurface flow in forest soils should not neglect the effect of root-induced macroporosity in the soil profile. In a similar type of forest, Whipkey (1969) measured subsurface flow after rainfall simulations. Through observations in trenches, Whipkey (1969) observed water leaking from root channels, with the greatest flow from channels just beneath or at an angle to the area where the simulations were carried out. The vegetation was composed principally of species with heart-shaped root systems (figure 4c), such as beech (*Fagus* sp.) and mature oaks (*Quercus* sp.), as well as species with more superficial plate-shaped root systems (figure 4e; Köstler et al. 1968) consisting of large or numerous lateral roots such as ash (*Fraxinus* sp.) and cherry (*Prunus* sp.). This mixture of species with different rooting patterns, with thick lateral roots in the proximity of vertical and oblique roots, can explain the high interconnection of water flow observed by Whipkey (1969). Similarly, Newman and colleagues (2004) observed lateral subsurface flow resulting from a melting snowdrift in a semiarid ponderosa pine (*Pinus ponderosa*) forest. All lateral subsurface flow occurred in the B horizon

and originated from macropores occupied by decaying or live roots. Only a few lateral roots were found in the C horizon. When soil conditions are not limiting, the ponderosa pine possesses a single long taproot with superficial widespreading lateral roots (figure 4d; Stoecklein 2001); therefore, subsurface flow along roots and channels occur mainly in the shallower soil layers.

Lateral subsurface flow was also observed by Noguchi and colleagues (1997a) in a Malaysian tropical rainforest dominated by *Koompassia malaccensis*, *Eugenia* spp., and *Canarium* spp. Noguchi and colleagues (1997a) found relatively high hydraulic conductivities in the upper layers of soil. Dyed water dispersed in the upper horizon and then percolated through vertical and downslope-oriented root channels. The root-system architectural type of *K. malaccensis* is not known, but *Eugenia* spp. and *Canarium* spp. generally possess roots mostly in the upper organic-rich layer of soil (Nishimura and Suzuki 2001, Ghani et al. 2009). This layer creates a porous zone in which high water pressures can develop from both saturated and nonsaturated flows. Noguchi and colleagues (1997b) also highlighted the similarity between the direction of subsurface flow and the direction of root growth in the upper layers of a semitropical forest dominated by *Cryptomeria japonica* and *Chamaecyparis obtusa*, two species with shallower, more plate-like root systems (figure 4e) that expand more on the uphill side of the stem (figure 3e). In deeper soil horizons, the direction of flow did not originate from root channels, because these were not numerous at that depth, but from soil cracks and weathered bedrock. Also in Malaysia, Collison and Anderson (1996) used a modeling approach applied to vegetation and soil data originating from long slopes. It was found that the roots of the tree species present did not usually cross the potential shear surface when they were growing in the middle of slopes with deep soils. Higher water pressures also resulted at the base of the rooting zone or even below this zone. Collison and Anderson's (1996) advice was that on such long slopes with deep soils, greater mechanical integrity will occur when trees are planted at the toe of the slope, where the potential shear surface is more likely to cross the rooting zone. Farther up the slope, grasses should be planted to reduce rainwater infiltration (figures 3i, 4a).

Although most case studies have been performed in forests, Cammeraat and colleagues (2005) studied hydrological processes on agricultural terraces on which rain-fed orchards—mainly cherries (*Prunus avium*), olives (*Olea europaea*), and almonds (*Prunus dulcis*)—were cultivated. These terraces in southern Spain were abandoned over 50 years ago and have since been colonized by shrubs such as gorse (*Ulex parviflorus*) and hawthorn (*Crataegus monogyna* Jacq.) and by Aleppo pine (*Pinus halepensis*), which has a taproot with long laterals and sinkers (figure 4d). Through a series of rainfall simulations, Cammeraat and colleagues (2005) observed that wetting fronts were more irregular and that percolation was deeper in the terraces that had been abandoned the longest. The increase in landslide occurrences was attributed to the faster transfer of rainfall to the potential slip plane by root channels. Although hawthorn has a shallow and wide-spreading root structure (figure 4e), which is probably not responsible for major preferential flow, stems can sprout directly from the lateral roots (figure 3k; Kutschera and Lichtenegger 2002). Therefore, juvenile plants can have relatively large and shallow roots that run continuously among stems underground. This type of root system can enhance lateral subsurficial flow. Aleppo pine possesses the large vertical taproot and thinner lateral roots typical of *Pinus* spp. (figure 4d); therefore, flow is likely to be greater along the thick taproot. This preferential flow along the thick taproot can create zones of high water pressure and, therefore, fragility at depth.

Species possessing superficial underground running stems and rhizomes (figure 3k) can also increase the likelihood of high pore pressures occurring just beneath the soil surface after heavy precipitation. Although Stokes and colleagues (2007) attributed the greater number of shallow landslides that occur in big-node bamboo (*Phyllostachys nidularia*) forests to poor root-system anchorage and superficial rhizomes that rarely traversed the potential shear surface, it is probable that dense root mats of rhizomatous bamboo species also have consequences for hydrological processes. Ide and colleagues (2010) found that during rainfall simulations in moso bamboo (*Phyllostachys pubescens*) forests, a high density of roots and rhizomes in the surface soil permitted a greater portion of rainfall to infiltrate into the soil. During heavy rain events, the dense root mats and thick rhizomes could even change the direction of rain flow, which resulted in lateral preferential flow. To a certain degree, this lateral flow ran out of the partially exposed roots and contributed to moderate amounts of surface runoff.

Even in peatland ecosystems, root channels can create discontinuities in the soil profile. Holden (2005) found that root channels of heather (*Calluna* spp.) increased the presence of macropores and the occurrence of bypass flow compared with cotton grass (*Eriophorum* spp.) and peat mosses (*Sphagnum* spp.) when they were growing on blanket peats. This increased flow was due to differences in the root architectures of these species: Heather possesses a woody and highly branched root system, whereas cotton grass has a prominent bulbous tussock root system composed of fine roots (figures 3i, 4a). Sphagnum moss cushions have no roots; only decaying litter material concentrates underneath these mosses.

One further highly complex environmental setting in which root architecture can interact directly and instantaneously with several different hydrological processes is a riverbank. To ensure the mechanical integrity of a riverbank, vegetation strips are widely planted by river managers, and careful consideration of what species to plant and how they should be planted is required. Simon and Collison (2002) gathered geotechnical, matrix suction, and pore-water-pressure data from streambank plots under three riparian covers: bare soil, eastern gamma grass (*Tripsacum dactyloides*) cover, and a mixture of mature trees composed

of *Platanus occidentalis*, *Liquidambar styroflora*, and *Betula nigra*. These authors demonstrated that after heavy rains, soil in plots with tree cover had positive water pressures, which counterbalanced the mechanical reinforcement of roots and could be detrimental to riverbank stability. The perennial eastern gamma grass has a superficial root system composed of numerous well-developed rhizomes and roots growing to a depth of 20 cm. Even if the concentration of root biomass was higher for eastern gamma grass than for the three tree species present on the plots, the roots of the tree species grew to a depth of over 80 cm. Preferential flow was thus initiated along these deep roots, and positive water pressures were created. Simon and Collison (2002) therefore demonstrated the potential for grasses to be used as effectively as trees to increase stream bank stability.

Conclusions

Because they have specific properties, organization, kinetics, and control factors, root channels represent a specific type of macropore. These characteristics of root channels need to be considered with reference to their influence on preferential flow. Root architecture analysis facilitates the upscaling of processes that occur at the individual plant root scale to processes that occur at the hillslope scale. Knowledge of root architecture at the hillslope scale is an important factor in addressing the complex nature of preferential flow, which has been demonstrated to influence landslide initiation (Sidle et al. 2001). Live and dead components of root systems can either promote or dissipate soil water pressure, depending on configuration, orientation, and interconnections; therefore they may either enhance or decrease the potential for shallow landslides during storms. Although ecological engineers are beginning to understand the benefits of the mechanical reinforcement of rooting systems, the potential effects of roots on subsurface flow should be given more consideration. As has been discussed in this article, several studies have made noticeable advances in the understanding of the effects of root channels on subsurface flow, but further research is still needed in order to better characterize the interactions among vegetation cover, root architecture, and the initiation of bypass flow. Some ideas for further research are developed in box 1. Such knowledge could significantly advance our insights into why certain hillslope segments fail during storms, whereas other segments remain stable.

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Box 1. Further research to better understand the effects of root channels on slope stability.

Studies to better understand the influence of root channels on slope stability are few, and slope failures often remain poorly understood. More focused research and suitable techniques are needed, especially concerning the geometry of the hydraulic passages provided by interconnected root channels. We need to consider the specific distribution of preferential flow paths, rather than the general influence of root systems and root channels on hydrological processes. Using tensiometers, Whipkey (1969) showed no appreciable change in hydraulic head at any time within the soil matrix. This result supports the observation that lateral flow was not moving as interflow through the general soil matrix but was moving, rather, through bypass channels. It is therefore unlikely that measurements of soil water pressures by tensiometers can demonstrate the existence of preferential flow paths. Dye tracers are probably one of the best ways to follow water movements in soils (see Flury and Wai 2003 for a description of useful dye tracers). Tracer-highlighted channels (particularly root channels) can then be observed *in situ* on trench walls and other excavations. X-ray-transmission-computed tomography, as well as resin and plaster impregnation, can also be used to analyze channel architecture in cores or blocks of undisturbed soil (Noguchi et al. 1997b).

In a field situation, parameters such as the presence of soil structural macropores, the homogeneity of the initial water content of the soil or the homogeneity of the bulk density of the soil are not easily controllable and can hamper the study of preferential flow through root channels. Therefore, one possibility would be to combine the use of tracers with laboratory measurements of soil shear in a large-scale Casagrande box. Real plants could be grown directly in shear boxes with controlled conditions of soil structure, soil texture, water content, and so on. Rainfall simulations in which stained water is used would allow for active channels to be identified on nonsheared control boxes and compared with active channels in sheared boxes.

Any step forward in our knowledge of root channels, such as knowledge of root-channel density, interconnectivity, and permeability, can bring useful insights for preferential flow modeling. A usual way to model preferential flow in soils is to consider a two-phase milieu: soil matrix and macropores. Although matrix flow is well known, macropore flow and, more particularly, root-channel flow still needs to be better characterized. The evolution of root-channel flow characteristics in response to temperature or precipitation changes could also be useful for improving the modeling of climate change impacts (Collison et al. 2000).

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Chapitre II

Partie II. 1.

► Ghestem. Relationships between root traits of plants growing on unstable slopes. En préparation.

Relationships between root traits of plants growing on unstable slopes

Abstract:

Background and aim: When assessing plant performance to resist failure during landslides, root tensile stress at failure is usually measured but other mechanical properties such as elasticity and capacity to recover after strain may also be important. Traits such as root construction cost, nutrient uptake capacity and survival should also be considered to assess the effective contribution of roots to slope stability. The aim of this study was to propose a coherent and non-redundant suite of root traits to investigate and manipulate in the future.

Methods: Mechanical, structural and chemical traits were measured on nine species present on a slope subjected to mass movement in Yunnan, China.

Main results and conclusions: We suggest concentrating on four measurements: root tensile stress, root tensile strain, nitrogen and water-soluble sugars contents. Root nitrogen content and respiration were well correlated with root mechanical resistance. This relationship may be a consequence of preferential growth in those roots which are most mechanically loaded on the slope undergoing slippage.

Key words: eco-engineering, root biomechanics, root chemical composition, root respiration, root tissue density, China

Introduction

When using vegetation to stabilize slopes subject to mass movement, mechanically strong roots are preferable. However, on unstable slopes which are often degraded and nutrient-poor,

root construction cost and longevity are also important. Plants which use a lot of energy to improve root mechanical resistance may not contribute as much to root construction and maintenance. Therefore, it is necessary to identify and quantify traits. A trait is a well-defined, measurable property of an organism, usually measured at the individual level and used comparatively across species. A functional trait is one that strongly influences organismal performance (McGill et al. 2006). Root longevity has been linked to several traits and in particular to chemical (nitrogen, carbon, water-soluble sugars, lignin and cellulose content), structural (diameter, root tissue density, specific root length *i.e.* root length per unit of dry mass) and physiological (respiration rates) traits: the function of short-lived roots is mainly to take up water and nutrients and they generally have a long specific root length, thin diameter, low tissue density, high water soluble compound and nitrogen contents, low carbon and lignin content and high respiration rates. Such roots are costly to maintain due to their high metabolism. Long-lived roots usually have a role oriented to anchorage, nutrient transport or storage. Traits are the opposite to those in short-lived roots and they are costly to construct (Ryan 1991, Ryan et al. 1996, Pregitzer et al. 1997, 1998 and 2002, Craine et al. 2001 and 2005, Tjoelker et al. 2005, Reich et al. 1992, 1997 and 2008, Kong et al. 2010, see Eissenstat et al. 2000 for a review). These relationships illustrate a trade-off between longevity and absorption capacity (Eissenstat and Achor 1999). Yet several contradictions exist; in particular nitrogen concentration may be positively collaborated with root tissue density (Kong et al. 2010). In some nutrient-poor environments, a high root tissue density associated with high nitrogen content suggests an adaptation for a longer duration of resource acquisition. There is no consensus on the influence of soil fertility on chemical, physiological and structural root traits. While in some studies chemical, physiological and structural root traits are not sensitive to the adding of resources (Kong et al. 2010, Ryser 2006, Pregitzer et al. 2002, Craine and Lee 2003 for root tissue density), in other studies, the differences observed

between chemical root traits are shown to be due more to habitat-induced differences than to any intrinsic difference between species (Martinez et al. 2002, Craine and Lee 2003 for chemical root traits). Under high nutrient conditions, roots may have a function of active nutrient uptake and assimilation, thus they have higher respiration rates and nitrogen concentration (Pregitzer et al. 1998) compared to roots growing in less fertile habitats which contain higher amounts of either waxes or lignin which are more expensive to synthesize than cellulose (Martinez et al. 2002). Under nutrient-poor conditions, initially fast-growing roots may in the long-term be competitively inferior to slow-growing roots (Ryser 1996).

Relatively little is known about the relationships between mechanical traits of roots and mechanical behaviour, particularly with regard to strain during loading. Many studies have focused only on ultimate strength at root failure to characterize root resistance. Yet the stress-strain behaviour of roots depends on several root mechanical traits (Fig. 1 and Table 1 for a list of biomechanical abbreviations). During the initial phase, the root strengthens, loses its tortuosity and is held in tension (Commandeur and Pyles 1991, Schwarz et al. 2010). As the root begins to resist the tension, deformation is reversible and is called elastic deformation (Niklas 1998). If the root is not broken at the end of elastic deformation, it enters a phase of non reversible deformation or visco-elastic deformation (Köhler et al 2000). This type of triphasic mechanical behaviour has been described for wood (Bodig and Jayne 1993) and animal tissues (Vincent 1990). For a similar ultimate tensile strength, a root possessing a short ultimate tensile strain would be more efficient in retaining soil slippage, compared to a root with a long ultimate tensile strain, as the surrounding soil has a shorter deformation capacity in tension than individual roots (Ekanayake and Phillips 1999, Docker and Hubble 2008). For a similar ultimate tensile strength, a root presenting a short – or non-existent – visco-elastic phase will be more efficiently remobilized in future conditions compared to a root with a long visco-elastic phase.

Little is known about the relationships between mechanical, structural and chemical root traits. Temperate tree root tensile strength was found to increase with increasing holocellulose content (Genet et al. 2005). Hathaway and Penny (1975) reported that variations in root tissue density explained variations in root stele tensile strength in *Populus* and *Salix* clones. These authors also also noted positive correlations between tensile strength and cellulose content in inter-clonal plants, as well as seasonal variations in the lignin:cellulose ratio. As cellulose is known to be more resistant than lignin in tension (Norris 2005), Hathaway and Penny (1975) explained this latter relationship by the action of of lignin under wet conditions. Root elastic modulus also has a positive correlation with cellulose content and a negative correlation with the lignin:cellulose ratio, demonstrating that roots with higher cellulose and lower lignin:cellulose ratios may require a larger force to align and break a greater number of cellulose chains (Hathaway and Penny 1975). However, lignin considered alone might also have a positive impact on root tensile resistance. When Hamza et al. (2007) altered lignin biosynthesis, they found that elastic modulus was lowered, but not the failure stress of tobacco (*Nicotiana tabacum* 'Samsun') roots. Several studies also showed an increase in elastic modulus with increasing lignin content in cell walls of stems (Hepworth and Vincent 1998, Köhler et al. 2000). Therefore, tensile strength and modulus of elasticity have been shown to increase with increasing root tissue density, cellulose and lignin content and to decrease with increasing lignin:cellulose ratio.

This paper aims at investigating whether relationships exist among mechanical root traits and more easily measurable chemical, physiological and structural traits. Examining these relationships, we wish to propose a coherent "package" of root traits to be examined when searching for robust and long-living roots to stabilize steep slopes.

Materials and methods

Site description

The study area (26° 01′ N, 98° 50′ E) was located near Daxingdi village, north of Liuku town in the Salween river valley. This part of China is under the influence of the Indian monsoon, described as a "warm–dry climate", and in a combination of subtropical and alpine climates. Annual mean temperature (from 1961 to 2002) is 15.2°C, and mean annual precipitation is 1200 mm, the majority of which falls between May and October (Ghestem et al. 2009). Numerous landslides occur during the monsoon season (May–October) and soil erosion is severe, largely due to the cutting of roads through the steep slopes (Stokes et al. 2010). Mountains around Daxingdi were covered by natural forests till the sixties, then deforested and planted with corn and cereals in the 1980s and 1990s. After several severe landslides destroyed slopes around the village, in the year 2000, degraded zones were included in reforestation programs initiated by the Chinese government (Stokes et al. 2010). Crop species such as Pueraria stricta, Jatropha curcas, Agava americana, Vernicia fordii, Ricinus communis were planted together with native species e.g. Artemisia codonocephala, Arthraxon hispidus, Chloris anomala, Bauhinia championii, Ficus tikoua, Rhus chinensis.. More than 70 species have been identified on these slopes. At our site, soil is a ferralitic silty clay, pH is basic and soil is not deep (clay bedrock at approximatively 50 cm deep). Soil is particularly unstable with an effective cohesion ranging from 0.49 to 5.35 kPa. However, nutrients are not particularly limiting, with an organic carbon content ranging from 12.31 to 28.7‰, total nitrogen content from 0.7 to 1.5‰ and cation exchange capacity from 43.81 to 51.51 cmol(+).kg-1 (unpublished data).

Mechanical tests

Roots were carefully hand-excavated from the whole soil profile and kept fresh in wet towels in the fridge until mechanical analysis. Tests were performed within the few hours after sampling using a portable machine (In-Spec 2200 BT, Instron Corporation, www.instron.com) equipped with three force transducers (max. capacity 250, 50 and 10 N, accuracy 0.25%) chosen according to the size of the root. Span tests were carried out for each species, confirming that the length of each sample had to be at least 30 times its central diameter to obtain reliable data (Cofie 2001). Root diameter was precisely measured at three points with a binocular microscope. Crosshead speed was kept constant at 1.0 $mm.min^{-1}$ and both force and speed were measured constantly via Instron Series IX software during each test. Tests were considered successful only when specimens failed in the middle third of the root and if the root did not slip inside the clamps because we were measuring both tensile stresses and strains. Approximately one test out of three was successful. In order to avoid slippage of roots out of the clamps, the clamps where chosen according to the diameter of the root and two pieces of emery paper were placed on either side of the root within the jaws of the clamp. Root samples were positioned as vertical as possible with their axes coinciding with the load cell axis. Tensile stress was calculated at each moment as the force supported by the root, divided by the root cross-sectional area (CSA) at the point of breakage. Tensile strain was calculated at each moment as the displacement divided by the total sample length. Each stress-strain curve was carefully analysed to obtain the mechanical properties of the root (Fig. 1).

Respiration measurement

CO_2 effluxes were measured on fresh and clean fine roots with a flux chamber apparatus (Licor Biosciences 6400-09, Nebraska, USA). Fine roots were defined as roots with diameter less than 2mm. Chamber temperature was controlled by a probe thermocouple and kept approximately constant for all measurements. Each sample was submitted to six successive

respiration cycles and only the three final data points were kept and averaged, as the three first data points were not on the curve's plateau.

Root tissue density

Within 24 hours after harvesting, roots were washed, paper-dried and scanned at a resolution of 700 dpi with an EPSON V700 Pro scanner. Image analysis was performed using WinRHIZO (Pro version 3.0, Regent Instruments, Canada, Zobel 2008) in order to obtain root length, diameter and volume. Roots were then dried at 60°C till constant weight and weighed (Mettler Toledo PB 203-N, precision 1 mg, maximum 210g). Root tissue density (RTD, $mg.mm^{-3}$) was defined as root dry mass/root fresh volume.

Carbon, nitrogen, water-soluble compounds and fibres extraction

Carbon (C) and nitrogen (N) concentrations were determined on dried roots with an elemental analyser (CHN model EA 1108; Carlo Erba Instruments, Milan, Italy). The concentrations of water-soluble compounds (SOL), hemicellulose (HCEL), cellulose (CEL) and lignin (LIG) were obtained by the Van Soest method (Van Soest 1963), and with a Fibersac 24 fiber analyser (Ankom, Macedon, NJ, USA). When the quantity of roots was enough, determination of root chemical composition was conducted on three replicates and averaged.

Statistical analysis

Linear relationships are assumed and correlation coefficients were calculated between traits. All significant relationships were checked by raw data graphs. Regressions were considered significant at $p<5\%$.

Results

Correlations between mechanical root traits

The majority of correlations were significant (Table 2). ε_t did not have high correlation with any of the other variables. T_{ult} and T_e were both highly correlated with E_e (r=0.83 and 0.85 respectively, Fig. 2a). T_{ult} was highly correlated with T_e (r=0.98) and ΔT_v (r=0.96; Fig. 2b). ε_{ult} was highly correlated with $\Delta\varepsilon_v$ (r=0.83, Fig. 2c) and with $\Delta\varepsilon_v/\Delta\varepsilon_e$ (r=0.84).

Correlations between chemical, physiological and structural root traits

Nitrogen (N) and carbon (C) contents were not correlated (Table 3a). C:N ratio was more correlated with N (r=-0.83) than with C (r=0.31, Fig. 3a). Water-soluble compounds (SOL) were negatively correlated with contents in each type of fibres, in particular with cellulose (CEL; Table 3b). Contents in fibres (HCEL, CEL and LIG) were not strongly correlated one with another: correlation coefficient between LIG and CEL was 0.27 but this relationship was not very clear especially for low values of LIG (Fig. 3b). Fibres, C and N were not highly correlated (Table 3c). The highest correlations were observed between C:N and SOL (r=0.36) and CEL (r=-0.32) but they were not obvious at low C:N values (Fig. 3c). RESP was well correlated with N (r=0.59) and C:N (r=-0.42, Table 3d). Root tissue density (RTD) was rather well correlated only with SOL, with a negative relationship (r=-0.37, Table 3e and f) but this relationship may be biased by a group of low RTD-high SOL data. An exponential-inverse relationship gave a better fit (Fig. 3d)

Correlations between mechanical and other root traits

Correlations between mechanical and structural properties were not very important (all r are < 0.34). Tortuous strain (ε_t) was not correlated with any trait. Fibres contents (HCEL, CEL, LIG) were not – or were poorly – correlated with mechanical traits.

For the elastic phase, N, RESP and RTD were positively correlated to Modulus of elasticity (E_e; r=0.32, 0.30 and 0.34 respectively) and elastic tensile strength (T_e; r=0.27, 0.29 and 0.36 respectively). SOL was negatively correlated with mechanical elastic traits. Elastic strain ($\Delta\varepsilon_e$) was positively correlated with C (r=0.24).

With regard to the visco-elastic phase: visco-elastic strain ($\Delta\varepsilon_v$) was negatively correlated with N (r=-0.27), RESP (r=-0.22) and RTD (r=-0.31). Also was $\Delta\varepsilon_v/\Delta\varepsilon_e$ (r=-0.31, -0.23 and -0.33 respectively). $\Delta\varepsilon_v/\Delta\varepsilon_e$ was positively correlated with SOL (r=0.21).

Ultimate tensile strength (ε_{ult}) was negatively correlated with N (r=-0.30) and RESP (r=-0.32). Ultimate tensile strength (T_{ult}) was positively correlated with RTD (r=0.34) and negatively with SOL (r=-0.28).

In conclusion, high N, RESP and RTD led to high moduli, high tensile strengths but short strains whereas high SOL content led to low moduli and tensile strengths, and long strains.

RTD seemed to be the non-mechanical trait that best correlated with mechanical root traits, and RESP was significantly correlated with mechanical traits in fine roots. Correlations between RTD and T_e, T_{ult} and ε_{ult} are shown in Fig. 4.

Discussion

Contribution of elastic and visco-elastic phases on root ultimate failure

Elastic and visco-elastic deformations did not depend on the length of initial deformation of strengthening. Ultimate load and strength were related to load and strength reached during the

elastic phase whereas ultimate deformation was more related to the increase of deformation in the visco-elastic phase. Therefore, the elastic phase impacted failure strength rather than strain, whereas the visco-elastic phase did not improve resistance but led to much longer deformations. To prevent against landslides, roots with a high elastic strength and modulus and no or short visco-elastic deformation would be preferred.

Unexpected relationships between mechanical and other traits

The positive relationship between water-solubles and nitrogen found by several authors (*e.g.* Craine et al 2005) was negative in our study. Moreover, roots which were the most resistant in tension, *i.e.* with high tensile strength, high stiffness and low visco-elastic deformation possessed a high root tissue density, high nitrogen content and high respiration rate (Table 4). Positive relationships between mechanical resistance and root tissue density were also observed in several studies (Craine et al. 2005, Hathaway and Penny 1975, Stokes et al. 2012 for stems). However, roots containing a high level of nitrogen are often associated with short-lifespans, and thus turnover quickly (Craine et al. 2005, Craine and Lee 2003, Scheurwater et al. 1998) suggesting poor mechanical properties. The inverse relationships shown in this study suggest that on a slope subject to substrate movement, a greater investment in those roots which contribute most to plant anchorage may occur.

In our study, root nitrogen content were low compared to values measured on tree roots from forests or plantations (Pregitzer et al. 2002, Pregitzer et al. 1997, Ryser and Lambers 1995) but are similar to values from studies carried out in grasslands (Kong et al. 2010, Craine et al 2005, Craine and Lee 2003). Root respiration rates were in the range of values found in other studies (Reich et al. 2008, Tjoelker et al. 2005). Root tissue density values also corresponded to those found in previous studies (Craine and Lee 2003, Ryser and Lambers 1995). Cellulose values are in the range of values found in the literature but hemicellulose and lignin contents were higher (Genet et al 2005, Martinez et al. 2002, Hathaway and Penny 1975). With regard

to mechanical values, ultimate tensile stress values were higher than those found for roots of several tree species (Docker and Hubble 2008, Tosi 2007, Genet et al. 2005 and 2008, De Baets et al. 2008). Nevertheless, Bischetti et al. (2005) measured ultimate stresses up to 730 kPa in temperate tree species. Similarly, the modulus of elasticity measured in our study was higher than those found by Fan and Su (2008), Tosi (2007), Cofie et al. (2000), Makarova et al. (1998), Waldron and Dakessian (1981), Hathaway and Penny (1975). Operstein and Frydman (2000) found maximum values of 13 MPa in *Medicago sativa* 'Gilboa' (Alfalfa). Root strain at failure was also longer than strains measured in other studies. This result could be due to an artefact of the testing method: we did not straighten the root before testing. In previous studies (Tosi 2007, Hathaway and Penny 1975, Cofie et al. 2000, Makarova et al. 1998), the initial tortuous phase of strain-stress curve was not integrated. Ultimate strains measured in our study reached 50% whereas in previous studies the maximum strain measured was 20%. Only Thomas and Pollen-Bankhead (2010) found strain values up to 35% but which were obtained by numerical calculation. If root nitrogen concentration and respiration rates are low but mechanical resistance is high, this association could be a strategy to optimize nutrient acquisition and root survival in unstable substrate conditions. Two mechanisms are possible: roots which have an efficient nutrient uptake may be preferentially reinforced mechanically by the plant; or high-acquisition roots may also directly transform resources into properties increasing mechanical resistance. If trade-offs occur, but are not between resource acquisition cost and mechanical reinforcement, they could be between e.g. a reduced number of roots or shorter roots. Root density per unit of soil and specific root length would be suitable traits for studying this question.

Choice of relevant traits when studying root efficiency to stabilize slopes

To stabilize steep slopes, roots have to be mechanically resistant, reversibly deformable and live long. Root traits to estimate these properties are many and may be too numerous to

measure. At this stage of the thesis, a selection of the most relevant traits can be proposed (Table 5).

Among traits measuring mechanical resistance, elastic tensile stress and visco-elastic strain can be privileged because:

- elastic stress represents the elastic phase better than elastic strain and represents stress at failure better than visco-elastic stress. Elastic stress is well correlated with modulus of elasticity and they are both good estimations of root ultimate resistance. Studying one will allow a good estimation of the other;
- visco-elastic strain gives a good idea of visco-elastic phase importance (rather than visco-elastic stress) and allows a good estimation of strain at failure (rather than initial or elastic strain).

If we do not have access to the stress-strain curve itself, measurement of ultimate stress can replace the measurement of elastic tensile stress and measurement of ultimate strain can replace the measurement of visco-elastic strain. Ultimate stress gives a good idea of elastic phase importance, while ultimate strain gives a good idea of visco-elastic phase importance.

Among traits measuring root metabolism, nitrogen content can be chosen over carbon because it allows a good estimation of carbon:nitrogen ratio and respiration rate.

With regard to root longevity, water-soluble sugars were negatively linked with all non-soluble sugars and root tissue density. Water-soluble sugars are simple to measure and thus could be a proxy for estimating root longevity (negative relationship).

Conclusion

In conclusion, our data from plant roots growing on steep slopes undergoing substrate movement showed that several root traits were significantly correlated within a same functional category:

(i) root ultimate tensile stress was significantly related to elastic tensile stress and modulus of elasticity

(ii) ultimate tensile strain was also correlated with the increment of strain during the visco-elastic phase

(iii) carbon:nitrogen ratio was negatively related to nitrogen content and cellulose content was negatively correlated to water-soluble compounds.

When interactions between functional categories were examined, correlations become less clear except for respiration rates which were related to nitrogen content. Nevertheless, some trends can be observed: root tissue density was relatively well linked with root mechanical resistance, as well as nitrogen content and respiration rates, indicating that the usually-observed trade-off between root tissue density and mechanical strength on one hand and respiration rate and nitrogen content on the other hand may not be observed for roots growing on nutrient rich but unstable conditions. To minimize root trait measurements we suggest concentrating on two mechanical measurements: root tensile stress and strain and two chemical measurements: nitrogen and water-soluble sugars content. All other root traits analyzed in this study and the associated functions can be reasonably deduced from these four traits.

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314

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Tables

Table 1

Mechanical properties and the abbreviations used in this study

Phase	Abbreviation	Meaning
Strenghtening	ε_t (%)	Strain of tortuosity
Elastic phase	E_e (MPa)	Modulus of elasticity
	$\Delta\varepsilon_e$ (%)	Increment of strain during the elastic phase
	F_e (N)	Tensile load at the end of the elastic phase
	T_e (kPa)	Tensile stress at the end of the elastic phase
Visco-elastic phase	E_v (MPa)	Modulus of visco-elasticity
	$\Delta\varepsilon_v$ (%)	Increment of strain during the visco-elastic phase
	ΔF_v (N)	Increment of tensile load during the visco-elastic phase
	ΔT_v (kPa)	Increment of tensile stress during the visco-elastic phase
Failure	ε_{ult} (%)	Ultimate strain at root breakage
	F_{ult} (N)	Ultimate tensile load at root breakage
	T_{ult} (kPa)	Ultimate tensile stress at root breakage
Curve shape	E_v/E_e (%)	Modulus of visco-elasticity on modulus of elasticity ratio
	$\Delta\varepsilon_v/\Delta\varepsilon_e$ (%)	Increments of strains during the visco-elastic phase on elastic phase ratio

Table 2

Correlation matrix between studied mechanical root traits. In italic: non-significant correlations. Framed: main significant correlations (r > 0.7)

	Tortuosity	**Elastic deformation**				**Visco-elastic deformation**				**Failure**			**Curve shape**	
n = 1095	ε_t (%)	E_e (MPa)	$\Delta\varepsilon_e$ (%)	F_e (N)	T_e (kPa)	E_v (MPa)	$\Delta\varepsilon_v$ (%)	ΔF_v (N)	ΔT_v (kPa)	ε_{ult} (%)	F_{ult} (N)	T_{ult} (kPa)	E_v/E_e (%)	$\Delta\varepsilon_v/\Delta\varepsilon_{ult}$ (%)
ε_t (%)	1.00													
E_e (MPa)	0.10	1.00												
$\Delta\varepsilon_e$ (%)	0.13	-0.27	1.00											
F_e (N)	-0.08	-0.14	0.54	1.00										
T_e (kPa)	0.16	0.85	-0.07	-0.09	1.00									
E_v (MPa)	*0.05*	0.40	-0.17	-0.09	0.39	1.00								
$\Delta\varepsilon_v$ (%)	-0.22	-0.23	-0.11	-0.14	-0.26	*-0.05*	1.00							
ΔF_v (N)	-0.14	-0.16	*-0.02*	0.23	-0.18	*0.00*	0.38	1.00						
ΔT_v (kPa)	*0.03*	0.29	-0.17	-0.13	0.27	0.54	0.31	0.13	1.00					
ε_{ult} (%)	0.09	-0.32	0.41	0.11	-0.24	-0.12	0.83	0.32	0.21	1.00				
F_{ult} (N)	-0.10	-0.17	0.51	0.98	-0.12	-0.08	-0.06	0.41	-0.10	0.17	1.00			
T_{ult} (kPa)	0.15	0.83	-0.11	-0.12	0.96	0.51	-0.14	-0.12	0.53	-0.15	-0.13	1.00		
E_v/E_e (%)	*0.00*	-0.13	-0.14	-0.08	-0.12	0.52	0.21	0.30	0.32	0.12	*-0.02*	*-0.01*	1.00	
$\Delta\varepsilon_v/\Delta\varepsilon_e$ (%)	-0.37	-0.24	-0.32	-0.20	-0.31	*0.05*	0.84	0.38	0.37	0.54	-0.12	-0.16	0.37	1.00

Table 3

a) Correlation matrix between carbon, nitrogen and C:N ratio; b) correlation matrix between water soluble components and fibres; c) rectangular correlation matrix between carbon, nitrogen and fibre contents; d) rectangular correlation matrix between carbon, nitrogen, fibres and root tissue density; e) rectangular matrix between carbon, nitrogen, fibres and respiration (only for fine roots); f) correlation matrix between fine root respiration and tissue density (only for fine roots). In italic: non significant correlations. Framed: main correlations in each matrix

a

n=179	N (%)	C (%)	C:N
N (%)	1.00		
C (%)	*-0.09*	1.00	
C:N	-0.83	0.31	1.00

b

n=227	SOL (%)	HCEL (%)	CEL (%)	LIG (%)
SOL (%)	1.00			
HCEL (%)	-0.52	1.00		
CEL (%)	-0.73	*-0.04*	1.00	
LIG (%)	-0.47	-0.20	0.27	1.00

c

n=172	SOL (%)	HCEL (%)	CEL (%)	LIG (%)
N (%)	-0.25	0.17	0.23	*0.14*
C (%)	*0.02*	*-0.03*	*-0.04*	0.15
C:N	0.36	-0.29	-0.32	*-0.09*

d

n=176	RTD ($mg.mm^{-3}$)
N (%)	*0.07*
C (%)	*-0.10*
C:N	*-0.14*
SOL (%)	-0.37
HCEL (%)	0.24
CEL (%)	0.26
LIG (%)	*0.12*

e

n=69	RESP ($nmolC.g^{-1}.s^{-1}$)
N (%)	0.59
C (%)	*0.18*
C:N	-0.42
SOL (%)	*0.18*
HCEL (%)	*0.20*
CEL (%)	*-0.20*
LIG (%)	*0.03*

f

n=111	RTD (mg.mm-3)
RESP ($nmolC.g^{-1}.s^{-1}$)	-0.22

475

476 Table 4

477 Rectangular correlation matrix between mechanical and structural root traits. In italic: non

478 significant correlations. Framed: main significant correlations (r > 0.20).

Mechanical traits \ Structural traits		n=1095			n=948		n=1095		n=1056	n=934
		N (%)	C (%)	C:N	SOL (%)	HCEL (%)	CEL (%)	LIG (%)	RTD ($mg.mm^{-3}$)	RESP ($nmolC.g^{-1}.s^{-1}$)
Tortuosity	ε_t (%)	0.08	0.09	*-0.02*	-0.15	*0.05*	*-0.01*	0.08	0.09	0.11
Elastic deformation	E_e (MPa)	0.32	-0.15	-0.22	-0.24	0.09	0.15	*0.00*	0.34	0.30
	$\Delta\varepsilon_e$ (%)	-0.12	0.24	0.13	*0.00*	0.16	*-0.02*	-0.11	*-0.05*	-0.12
	F_e (N)	*-0.05*	0.19	0.11	*0.01*	0.16	*0.01*	-0.14	0.08	*0.03*
	T_e (kPa)	0.27	-0.14	-0.17	-0.28	0.10	0.18	*0.00*	0.36	0.29
Visco-elastic deformation	E_v (MPa)	*0.03*	-0.12	*0.01*	-0.15	*0.03*	*-0.03*	*0.01*	0.27	0.12
	$\Delta\varepsilon_v$ (%)	-0.27	*-0.04*	0.14	0.15	-0.10	-0.08	*0.01*	-0.22	-0.31
	ΔF_v (N)	-0.14	0.10	0.15	0.08	-0.07	*-0.01*	*-0.03*	*-0.04*	-0.27
	ΔT_v (kPa)	-0.11	-0.17	*-0.02*	-0.11	*0.01*	-0.07	0.08	0.11	-0.16
Failure	ε_{ult} (%)	-0.30	0.10	0.20	0.11	*0.00*	-0.08	*-0.03*	-0.21	-0.32
	F_{ult} (N)	-0.07	0.20	0.14	*0.02*	0.14	*0.00*	-0.14	0.07	*-0.06*
	T_{ult} (kPa)	0.21	-0.17	-0.14	-0.28	0.09	0.14	*0.02*	0.34	0.21
Curve shape	E_v/E_e (%)	-0.17	*-0.02*	0.15	0.06	-0.12	*-0.04*	*0.05*	*0.00*	*-0.03*
	$\Delta\varepsilon_v/\Delta\varepsilon_{ult}$ (%)	-0.31	-0.10	0.14	0.21	-0.16	-0.13	*0.04*	-0.23	-0.33

479

480

481 Table 5

482 Main traits to be measured to assess root efficiency on slope stabilization. +: positive correlation, -: negative correlation

Trait category	Trait	Traits which are co-evaluated	Functions estimated	Function positive or negative for slope stabilization?
Mechanical traits	Ultimate stress	+ modulus of elasticity, + elastic stress, + root tissue density	High tensile strength and stiffness, long reversible deformation	Positive
	Ultimate strain	+ visco-elastic strain, + visco-elastic on total strain ratio	Long non-reversible deformation	Negative
Chemical traits	Nitrogen content	- carbon, C:N ratio, + respiration rate	High metabolism (high nitrogen acquisition and respiration)	Positive
	Water-solubles	- fibres, - root tissue density	Low construction cost / low survival	Positive/Negative

483

Figure captions

Fig. 1

Stress-strain curve characterizes deformation and failure behaviours of each root. See Table 1 for a list of abbreviations used on this figure

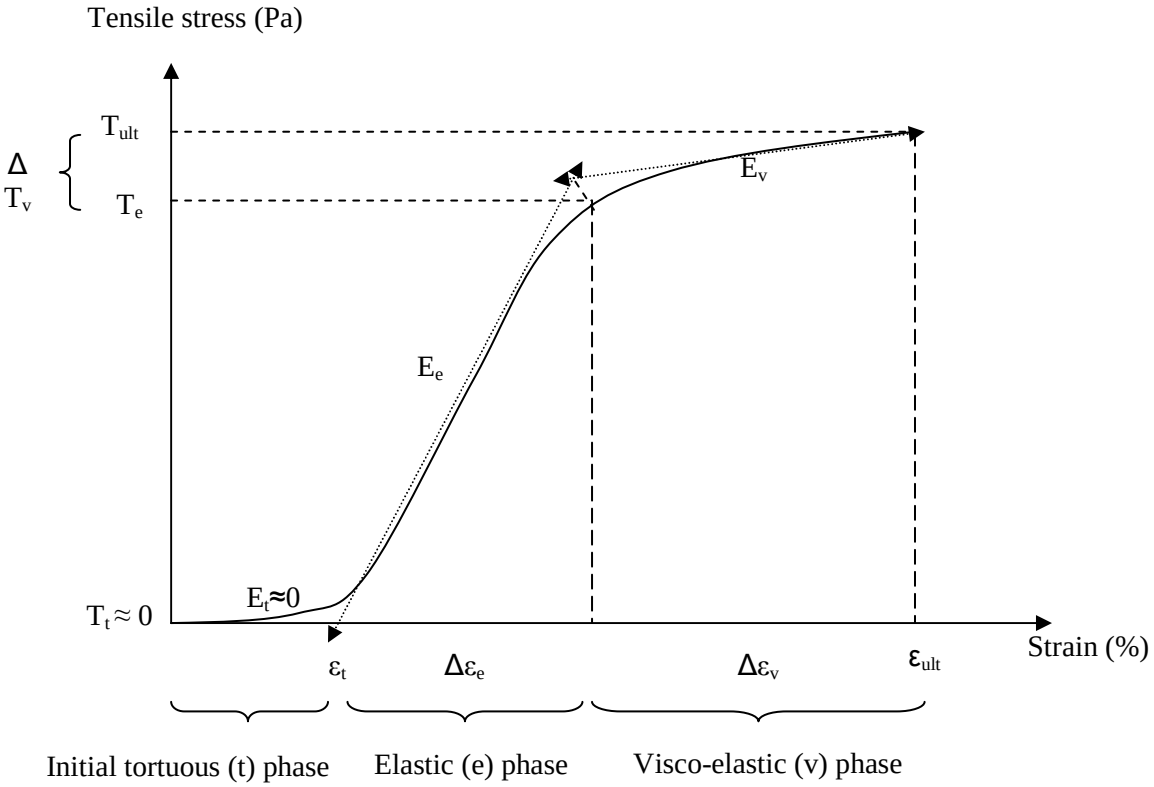


Fig. 2

a) Increment of strain during elastic phase ($\Delta\varepsilon_e$) and modulus of elasticity (E_e) in function of the tensile stress at the end of the elastic phase (T_e which equals $\Delta\varepsilon_e$ * E_e): T_e is more correlated with E_e than with $\Delta\varepsilon_e$; b) T_e and the increment of stress during the visco-elastic phase (ΔT_v) in function of the ultimate stress at failure (T_{ult} which equals T_e + ΔT_v): T_{ult} is slightly more correlated with T_e than with ΔT_v. and c) $\Delta\varepsilon_e$ and the increment of strain during visco-elastic phase ($\Delta\varepsilon_v$) in function of ultimate strain at failure (ε_{ult}, which equasl ε_t + $\Delta\varepsilon_e$ + $\Delta\varepsilon_v$): ε_{ult} is more correlated with $\Delta\varepsilon_v$ than with $\Delta\varepsilon_e$

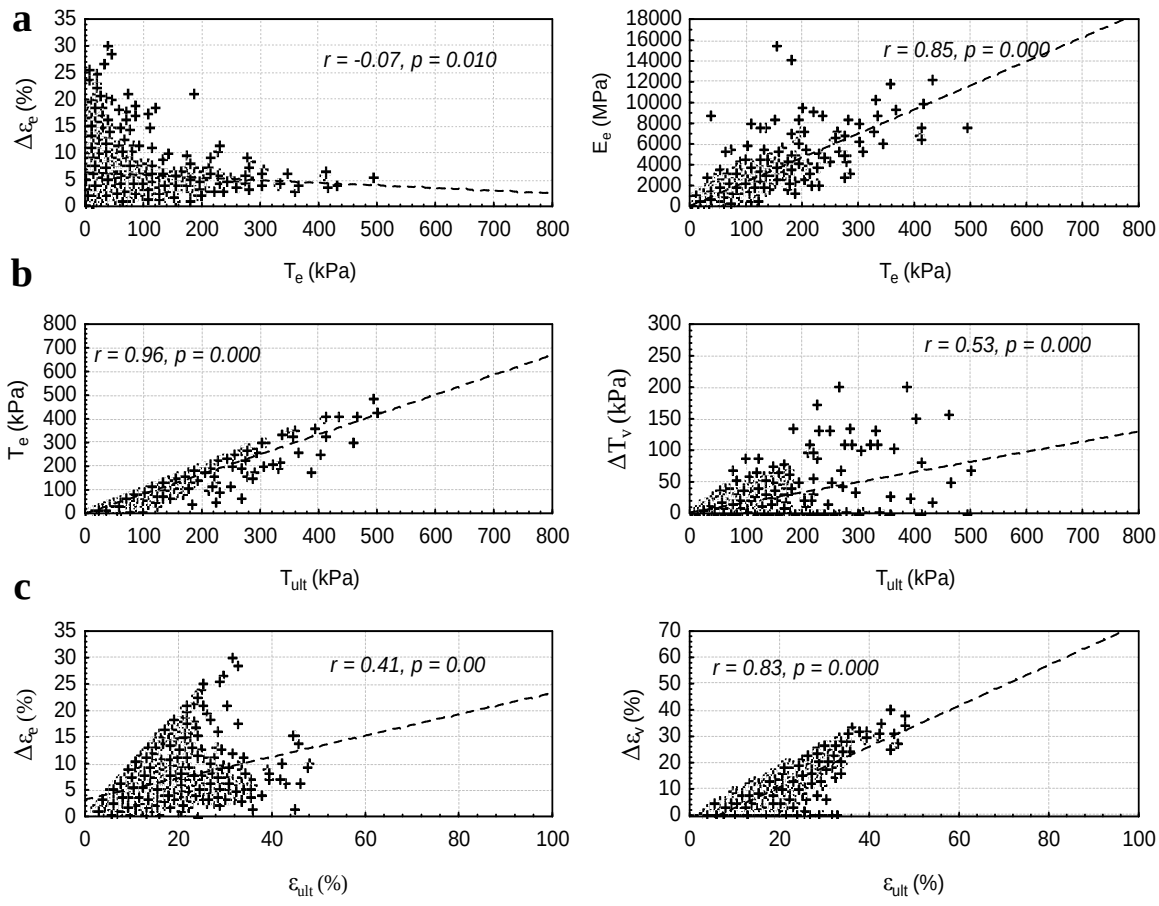


Fig. 3

Relationships between a) C:N, nitrogen (N) and carbon (C); b) lignin (LIG), cellulose (CEL) and hemicellulose (HCEL); c) C:N, water solubles (SOL) and cellulose and d) root tissue density (RTD) and water soluble compounds

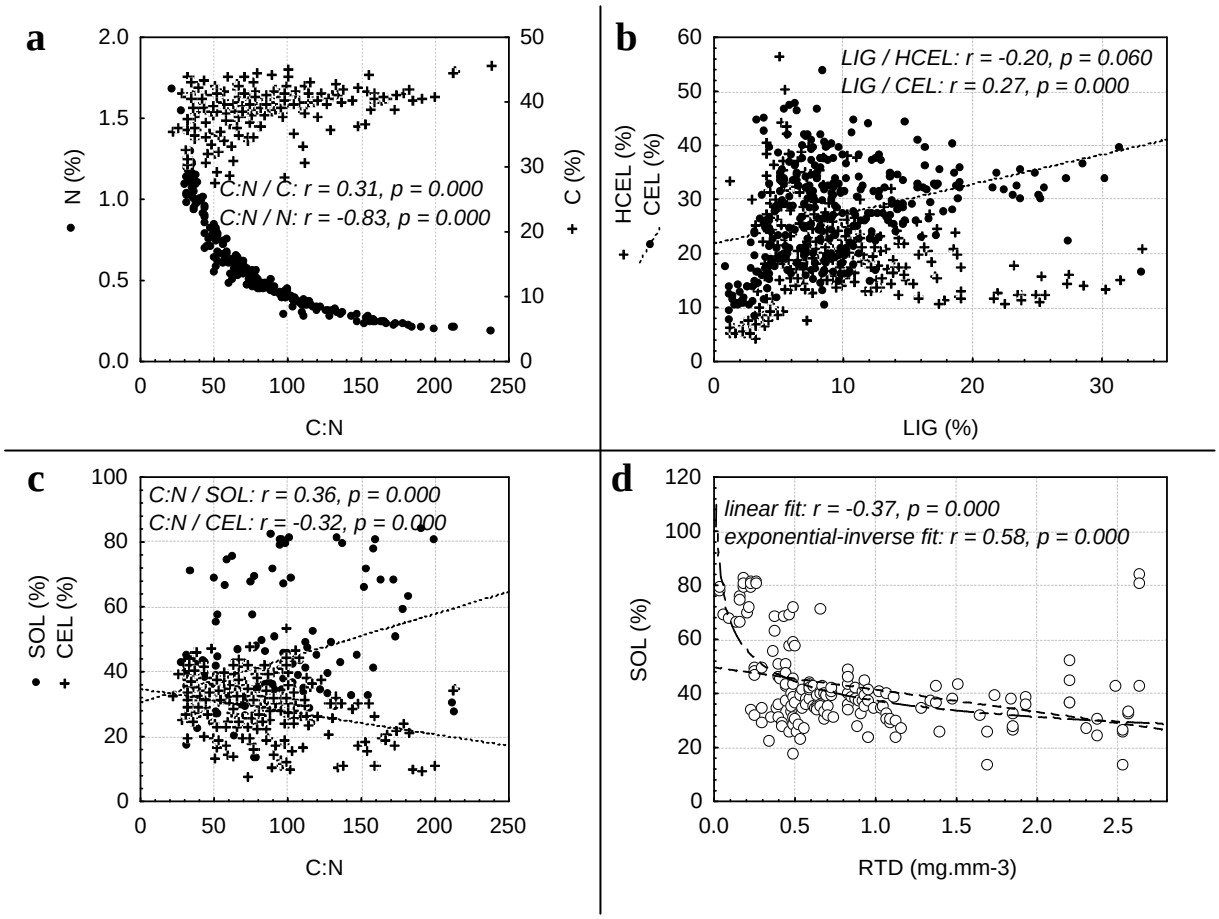
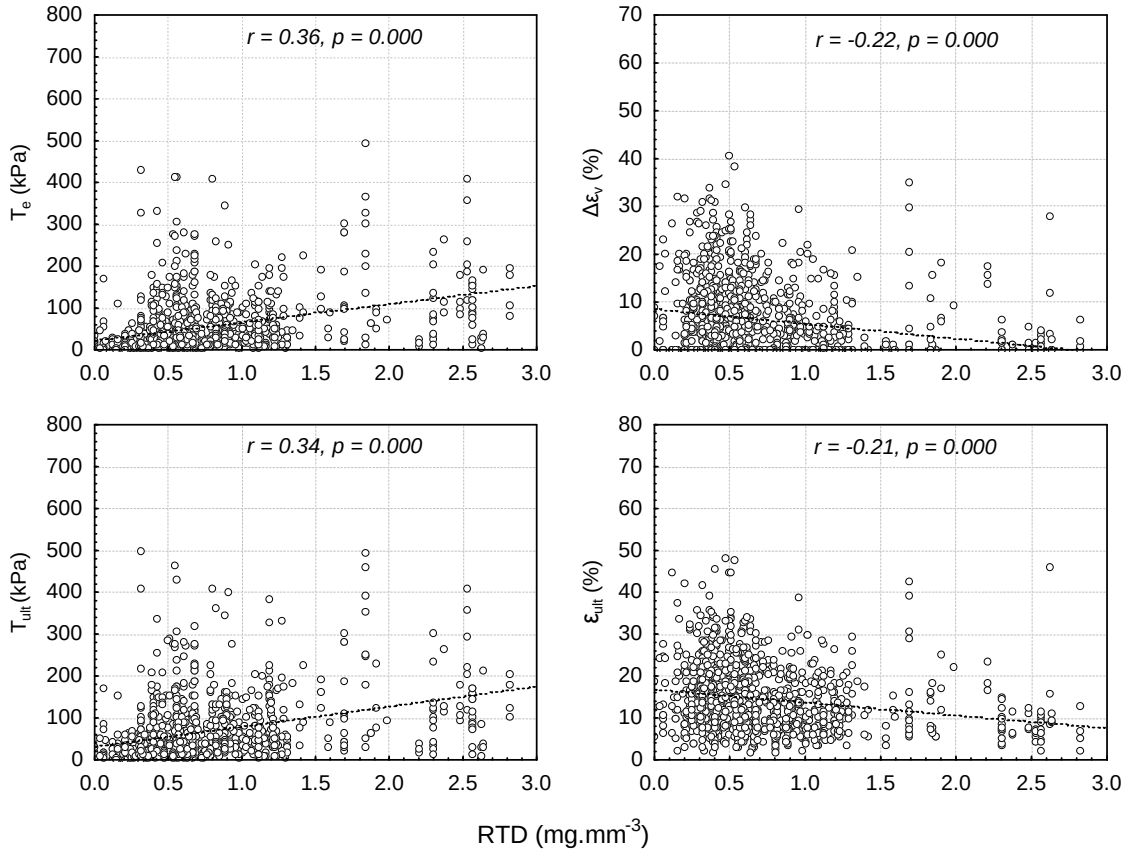


Fig. 4

Relationships between root tissue density (RTD) and a) tensile strength at the end of elastic phase (T_e); b) strain increase during visco-elastic phase ($\Delta\varepsilon_v$); c) ultimate tensile strength (T_{ult}) and d) ultimate strain (ε_{ult})



Chapitre II

Partie II. 2.

► Ghestem, Stokes. Which plants can be used as ecological engineers to fix soil on unstable slopes? En preparation pour Restoration Ecology.

Which plants can be used as ecological engineers to fix soil on unstable slopes?

Abstract:

Goals: Reforestation programs have been initiated on wide sliding surfaces in southern China but knowledge is lacking on which plant species are the most efficient at young stages to stabilize degraded zones. This study aims at identifying which species could be used as "tools" for eco-engineering actions.

Methods: Nine species were selected at two sites: one site stabilized eight years ago by planting and a still sliding site. Stem densities were counted, young individuals were entirely hand-excavated to measure precisely their root system volume, root area density, root tensile stress and strain, root stiffness in bending, root nitrogen concentration and root water-soluble sugars at each depth and upslope and downslope from the stem. The effects of site, season, root diameter, root depth and root position from the stem were studied.

Principal results and major conclusions: *Pueraria stricta* (Leguminosae), a planted small tree native from South-East Asia, and *Artemisia codonocephala* (Asteraceae), a spontaneous biannual, seemed the most efficient species. The two species seem to be efficient even on still-sliding slopes, and are thus good candidates for slope short-term restoration. We could recommend planting or encouraging *P. stricta* at the top and *A. codonocephala* at the toe of the hotspot. We would draw practionners' attention when planting *Agava americana* (Asparagaceae) and *Jatropha curcas* (Euphorbiaciae): they do not appear to be the best candidates to stabilize slopes against landslides.

Key words: landslides hotspot, eco-engineering, root architecture, biomechanics, China

Introduction

Eco-engineering has been defined as the long-term, ecological strategy to manage a site with regard to natural or man-made hazards (Stokes et al. 2010). Vegetation has long been recognized as useful for increasing slope stability with regard to shallow landslides (Greenway 1987). To improve slope stability, managers do not necessarily need to stabilize the whole slope, but in certain cases, could focus only on relatively small areas, or 'hotspots' (Baigorria & Romero 2007). With regard to soil erosion, these areas are defined as sites with soil erosion rates well above soil loss tolerance levels (Poesen et al. 2008). Hotspots often only occupy a small fraction of a catchments' area, but may be held responsible for a very significant contribution to overall sediment production, thus leading to off-site problems (Poesen et al. 2008). Reducing erosion or soil slippage on hotspots via an appropriate species or mixture of species might be an economic and efficient method to protect against large-scale landslides. However, which species or mixture of species would be suitable would depend on local soil and climatic conditions. The appropriate plant characteristics for fixing soil in hotspots would also need to be determined, as well as the optimum spatial positions of species within a hotspot.

If plants could be used as 'ecological engineers,' i.e. can be used to design a sustainable ecosystem that have value to both the environment and society (Mitsch 2012), the best species for slope stabilization would be native, combine economic value, have extensive and deep root systems with strong and fast-growing roots that are slow to decompose. Plant root systems can be described using suites of traits. A trait is a well-defined, measurable property of an organism, usually measured at the individual level and used comparatively across species. A functional trait is one that strongly influences organismal performance (McGill et

al. 2006). Lists of desirable root system traits for fixing soil on slopes are available (Burylo et al 2009, Stokes et al 2009, Ghestem 2012, this thesis). The most commonly used are root area ratio (RAR), which is the surface area of roots over a given area of soil and root tensile strength. These traits are used to calculate additional cohesion (Waldron 1977; Wu et al. 1979; Ghestem et al. 2009; Genet et al. 2010). However, it has recently been shown that the mechanical behaviour of roots, with regard to strain during tensile loading, should also be considered in order to calculate more realistic values of additional cohesion (Köhler et al. 1999; Pollen and Simon 2005, Schwarz et al. 2010).

Strain in a root held in tension is basically composed of three phases: an initial phase of stretching followed by a phase of reversible deformation called the elastic phase, which is sometimes, but not always, followed by a phase of irreversible deformation called the visco-elastic phase. Ghestem (2012, this thesis) showed that the maximal tensile strength required to cause root failure is representative of the elastic behaviour and represents the capacity of a root to deform reversibly, while the ultimate tensile strain is representative of the irreversible deformation of a root. To improve slope stability, roots with a high tensile strength and a small tensile strain would be most efficient, because soil can bear only a very small displacement before it ruptures (Ekanayake & Phillips 1999; Docker & Hubble 2008, Ghestem et al., this thesis). The irreversible phase of deformation should also be as small as possible because roots which can be re-mobilized will be more efficient in the long-term.

In most previous studies whereby the contribution of vegetation to slope stability was examined, only tensile strength of thin and fine roots was considered. Yet, thicker roots act as soil nails, pinning the root systems into the substrate. Therefore, Wu and Watson (1998) stipulated the importance of also measuring bending stiffness, so that they could be incorporated into slope stability models (Nakamura et al 2007).

Further characteristics which need considering when choosing species to act as ecological engineers on hotspots, include the ability of a species to colonise a slope, the individual soil volume occupied by a root system and the quantity of roots within this volume. The individual soil volume is the root system's overall envelope, given by its maximum radius (horizontal extension) and its maximum depth (vertical extension; Oppelt et al. 2005 a and b, Hughes et al. 1995). Root quantity can be represented by the root area ratio (RAR).

In disturbed environments such as hotspots, root mechanical traits should be considered alongside root longevity and root metabolism, i. e. nutrient uptake. Root longevity and metabolism have been shown to be correlated to several traits e.g. nitrogen, carbon, water-soluble and non-soluble (hemi-cellulose, cellulose, lignin) sugars as well as root thickness, root tissue density, specific root length (SRL, root length per unit of dry mass) and root respiration (see Eissenstat et al. 2010). Ghestem (2012, this thesis) measured suites of these traits in several species and showed that nitrogen content was a good proxy of root metabolism and that water-soluble sugars content was a suitable proxy of root lifespan (inverse relationship: high content of water-soluble sugars induces low lifespan). Root ability to recover during a landslide can be estimated by its ultimate tensile strain: the shorter its ultimate tensile strain, the shorter its irreversible phase of deformation (Ghestem 2012, this thesis). Thus if its ultimate tensile strain is short, the root will principally bear reversible deformation. Very few studies have examined such traits in the context of slope stability analyses (Ziemer & Swanston 1977; Phillips & Watson 1994), because most studies focussed on mechanical root traits linked to additional cohesion.

In order to determine plant species useful for engineering slope stability, we analysed mechanical and chemical traits of roots growing along a highly degraded slope in southern China. The number of shallow landslides in China has increased enormously over the last 50

years, due mainly to deforestation, infrastructure and road construction (Yin 2008, Stokes et al. 2010). The Chinese government has therefore launched a major landslide inventory named "monitoring and preventing of landslides by masses" (Yin 2008) and two afforestation programs: the Natural Forest Protection Program (NFPP) and the Sloping Land Conversion Programme (SLCP or Grain for Green programme, which aims at planting trees on existing agricultural land, concentrating on zones where slopes are >25°; Xu et al. 2006; Stokes et al. 2010). The results of these two programs are contrasted (Pearce 2001; Xu & Cao 2001; Brown et al. 2001; Liu 2002; Yu et al. 2002; Sun et al. 2004; Kahrl et al. 2004 and 2005; Xu al. 2006; Zackey 2007; Wang et al. 2007; Bennett 2008). Case studies recorded high seedling mortality where tree species used for replanting were not suitable for the local environment (Weyerhaeuser et al. 2005; Trac et al. 2007), degradation of local population welfare (Huang et al. 2004), more surficial erosion (Fattet et al. 2011) and increased slope instability (Genet et al. 2008). Within such a major socio-economic context, information on how species can be used to engineer slope stability is vital, especially during the early years of after plantation on a bare slope, when the window of landslide susceptibility is greatest (Sidle and Hornbeck 1991).

We discuss therefore, how plants can be used as ecological engineers, through a better understanding of plant traits and the optimising of species mixtures and planting patterns on degraded slopes.

Material and methods

Study site

We studied root morphological, mechanical and chemical traits for species growing in the Yunnan province, Southern China, where erosion and landslides are severe (Zhou et al. 1998). The study area (26°01'N, 98°50'E) was located near Daxingdi village, north of Liuku town in the Salween river valley. This part of China is under the influence of the Indian monsoon, and described as a "warm-dry climate", being is a combination of subtropical and alpine climates. Annual mean temperature (from 1961 to 2002) is 15.2°C, and mean annual precipitation is 1200 mm, the majority of which falls between May and October (Ghestem et al. 2009; Fattet et al. 2011). Numerous landslides occur during the monsoon season (May-October) and soil erosion is severe, largely due to the cutting of roads through the steep slopes (Stokes et al. 2010). We carried out fieldwork in 2009 and 2010. In 2010, precipitation during the summer months was particularly high (Fig. 1) and shallow landslides throughout the area were numerous. At our study site, corn (*Zea mays*) was cultivated from 1980, after deforestation, until 1999 when the SLCP was initiated. Several species of trees and shrubs were planted at the site, including *Pueraria stricta*, *Ricinus communis*, *Agava americana*, *Jatropha curcas*, and *Vernicia fordii*.

We identified two sites: one site was an active landslide approximately 30 m wide and 50 m long. The origin of the landslide may have been due to severe erosion leading to gully formation and eventual soil slippage. As soil slippage at this site was active, we considered it as a degradation hotspot. The second site was located at 3 m from the landslide where a shallow landslide had occurred at this site in 2000, after an extreme precipitation event. Since 2000, trees and shrubs have been planted within the SLCP and pioneer species have colonized the site naturally. This latter site appears to have been stabilized through vegetation cover, therefore we presumed that it was 'stable.' The two sites were located at an altitude of 1010 m.

Slope angle was 35-45° at the hotspot and 50-60° at the stable site. Both sites were oriented at 300° from due north. Plots were identified within each site: at the stable site, plot size was 1000 m^2 and at the hotspot, plot size was 600 m^2.

Soil characteristics

Soil profiles

We determined soil profiles at the hotspot, stable site and also at a third site. This site was situated 200 m from our sites at same altitude and was used for comparison. This third site was considered highly stable because no evidence of previous landslides or erosion was found. Soil profiles to a depth of 1.0 m were examined at each site and described using colour charts (Munsell 1947). Potential shear surfaces were identified as the limit between soil and bedrock horizons. Soil was a ferrallitic red carbonated soil with many mineral coloured spots, e.g. iron and manganese. In the stable site with no previous evidence of a landslide, soil thickness was 0.7 – 2.0 m, and the depth at which emerged the source rock (limestone) and humus thickness was <1 cm. Humus was classified as a mesomull (Baize 1995). Source rock (limestone) emergence occurred at 0.5 m at the hotspot and 0.4 m on the stable site where a landslide had occurred 8 years previously (Fig. 2).

Soil texture and chemical characteristics

Soil texture and chemical characteristics were measured at the hotspot and stable site on eight samples taken randomly throughout each plot from representative typical A- and at B-horizons i.e. at 0.05 m and 0.35 m. Soil analyses were carried out on soil fractions finer than 2 mm. Sand (2.00-0.05 mm), silt (0.050-0.002 mm), and clay (<0.002 mm) contents were determined using the sedimentation and sieving method (Table 2, NF P 94-056 and 94-057, AFNOR 1996). Soil pH was measured using a potentiometry method (LY/T1239-1999, Kalra & Maynard 1991), cation exchange capacity (CEC) was measured using the distillation

171 method (LY/T1243-1999) and soil carbon (C) and nitrogen (N) contents were measured using
172 a C-N analyzer (Thermo-Finnigan CHN analyser). The two sites possessed similar basic pH
173 and CEC values (Table 2). CEC was high compared to typical values of soils containing 50%
174 clay (Baize 2000), indicating a high potential fertility. C and N concentrations (Table 2) were
175 similar to those found in forest or pasture soils (Baize 2000). Organic carbon, representing
176 organic matter (OM=OC*1.7; Baize 2000), was more abundant at the hotspot compared to the
177 stable site. The proportion of organic carbon on total nitrogen was higher at the hotspot
178 compared to the stable site, indicating that mineralisation of organic matter was slower at the
179 hotspot. Therefore, nitrogen resources might be limiting at the hotspot. No statistical analyses
180 were performed because of too few data.
181 Soil physical characteristics
182 A manual shear tore vane (IMG I01 025, www.img.fr) was used to estimate soil shear
183 strength in situ at a depth of 0.20 m at 20 randomly located positions within each plot (Table
184 2). A manual penetrometer (Elmeg PEN-3960, www.elmeg.org) was also used to estimate
185 penetration at a depth of 0.20 m at 20 locations within each plot. Strain-controlled direct shear
186 tests were carried out on eight reconstituted, drained 60 mm x 60 mm x 20 mm soil samples
187 from each site and each horizon. Roots were removed during the reconstitution process (Fattet
188 et al. 2011). Samples were not saturated prior to testing, and as they were kept sealed at 4°C
189 after removal from the field, it can be assumed that soil moisture content was similar to that in
190 field conditions. Samples were placed in a shear testing device (VJTech 2760A,
191 www.vjtech.co.uk) and normal loads of 200, 300 and 500 N were applied as weights on three
192 separate samples taken from the same block of soil (Schuppener et al. 1999). A lateral
193 displacement was applied at a speed of 0.8 mm min^{-1} until failure occurred and the peak shear
194 force recorded. The cohesion (C) and the angle of internal friction (Φ) were obtained by the
195 Mohr-Coulomb theory (Schuppener et al. 1999). To obtain soil initial moisture content (w_i),

soil moisture content at saturation (w_s) and soil dry bulk density (ρ_d), a modified method from Baize (2000) was used on seven samples at the two sites (in 2009) and at A and B horizons (in 2010). First, samples were weighed while they were fresh (m_i, initial mass). Samples were then dipped in paraffin and the volume of water occupied by the sample measured in a graduated cylinder (v, soil volume). Samples were then saturated with water and weighed (m_s, saturated mass), before drying at 105°C until constant weight (m_d, dry mass).

$$w_i(\%) = (m_i - m_d) * 100 / m_d \quad \text{Eq. 1}$$

$$w_s(\%) = (m_s - m_d) * 100 / m_d \quad \text{Eq. 2}$$

$$\rho_d = m_d / v \quad \text{Eq. 3}$$

Choice of species

A species inventory was carried out in 2008 and 60 species indentified (Appendix). A large documentation was gathered from the literature, field observations and discussions with local people. To select species, two necessary criteria were required: the species must be present on landslides and allow other species to establish, i.e. it must not be invasive. Among species answering to those two criteria, ecological characteristics were considered e.g. lifespan, rooting type (through visual observations) and lifeform. Any economic and ethnobotanical properties were noted e.g. food and fodder use, medicinal purposes, fertilizer, fuel or handcrafts. Species were then classified according to these properties (Appendix). We selected nine species (Fig. 3): *Agava americana* L. (Asparagaceae), *Arthraxon hispidus* (Thunb. ex Murray) Makino (Poaceae), *Artemisia codonocephala* DC. (Asteraceae), *Bauhinia championii* Benth. (Leguminosae), *Chloris anomala* B. S. Sun & Z. H. Hu (Poaceae), *Ficus tikoua* Bureau (Moraceae), *Jatropha curcas* L. (Euphorbiaceae), *Pueraria stricta* Kurz. (Leguminosae), *Rhus chinensis* Miller (Anacardiaceae). All species were pioneers and present

on both plots at the beginning of the rainy season, when slopes were more prone to landslides. Species were not invasive and were of economic value for the local population, as well as representing different lifeforms (Fig. 3).

Plant abundance

In August 2009 and July 2010, the density of each species present at both sites was measured in two transects along the slope. Within each transect, we measured species composition in eight 1m² quadrats every 4 m along the transect. Within each quadrat, we counted the number of individuals of each species and the percentage of soil covered by the vertical projection of the canopy at a height of 30 cm above the soil surface.

Choice of individuals

Plant height and stem basal diameter were measured (Table 3), but are not indicative of age because of occasional cattle grazing. By comparing individuals with reference plants that germinated during the 3 years we worked at the site, we estimated that the individuals we studied were 3-6 years old. For each species, the root systems of 12 individuals were excavated by hand (n = 6 at each site, Fig. 4). Excavations were carried out with extreme caution, so as to not damage root systems. All individuals were chosen within the same size range (Table 3).

During excavation, (x, y, z) coordinates of all structural roots were measured, along with the points of root emergence, tips and forks, and their distance from the root-stem base. The orientation of roots in a circular sector was considered qualitatively. All roots in the upper half of the sector, with regard to slope direction, were noted as upslope roots, and those in the lower sector noted as downslope roots. Roots were also classed into depth classes of 10 cm

243 perpendicular to the soil surface. During excavation, roots were covered with wet towels to
244 prevent desiccation. Root systems were then transported to the laboratory and stored at 4°C.
245

246 ## Individual soil volume and root area ratio

247 Soil volume was calculated as the corresponding portion of individual soil volume (ISV) in
248 each 10 cm layer of soil and in each upslope or downslope sector. Spatial x, y, z coordinates
249 of each structural root allowed us to estimate the maximum radius and depth of each root
250 system. Using these coordinates for each plant, ISV was calculated as a quarter of ellipse
251 upslope plus a quarter of ellipse downslope, with the size of the ellipse determined by the
252 maximum radius and depth. However, in *A. americana* and *F. tikoua*, root systems were
253 organised linearly along the main plant stem (Fig. 4). Therefore, the ISV of these species were
254 calculated as a quarter of a cylinder upslope plus a quarter of a cylinder downslope. The
255 maximum radius and ISV volume for each soil layer were deduced from geometrical
256 equations. Standardizing ISV by the collar diameter allows plant individuals of different sizes
257 to be compared (Burylo et al. 2009).
258 Root area ratio is the cumulated cross sectional area (CSA) of all roots crossing the potential
259 shear surface per unit of soil surface. RAR can also be calculated as the cumulated volume of
260 roots per unit of soil volume, if we consider that all roots within a layer cross the surface of
261 this layer perpendicularly (Genet 2007).

262 $$RAR = \left(\sum_{i=0}^{j} CSA \right) / A = \left[\left(\sum_{i=0}^{j} CSA \right) * h \right] / (A * h) = V_r / V \qquad \text{Eq. 4}$$

263 where $\sum_{i=0}^{j} CSA$: sum of CSA by classes of diameter [0; j] of all roots crossing a soil surface *A*,
264 *h*: height of the considered layer, V_r: cumulated volume of roots within the corresponding
265 volume of soil *V*.

RAR was calculated for roots separated into two diameter classes: fine]0; 2mm[, and coarse [2mm; +∞[. Within 24 hours after harvesting, roots were washed, paper-dried and scanned at a resolution of 700 dpi using an EPSON V700 Pro scanner. Root length, diameter and volume were measured using the image analysis software WinRHIZO (Pro version 3.0, Regent Instruments, Canada; Zobel 2008) within each 10 cm depth class and within up- and down-slope sectors.

Mechanical tests

After scanning, and also within 24 hours after harvesting, tensile testing of a sub-sample of individual roots was performed for each species. Testing was successfully carried out on 1116 roots, using a portable testing machine (In-Spec 2200 BT, Instron Corporation, www.instron.com) equipped with three force transducers (maximum capacities of 250, 50 and 10 N and accuracy of 0.25%) chosen according to the size of the root. Span tests were carried out for each species to check that the length of each sample had to be at least 30 times its central diameter (Cofie 2001). Root diameter was measured at three points along each root using a binocular microscope and the mean diameter calculated. Crosshead speed was kept constant at 1.0 $mm.min^{-1}$ and both force and speed were measured constantly via Instron Series IX software during each test. Tests were considered successful only when specimens failed in the middle third of the root and if the root did not slip inside the clamps, because we were measuring tensile stresses as well as tensile strains. In order to avoid slippage of roots out of the clamps, the clamps where chosen according to the diameter of the root and two pieces of sandpaper were placed on either side of the root within the jaws of the clamp. Tensile stress was calculated as the force required to cause breakage, divided by the root CSA at the point of breakage. Tensile strain was calculated as the displacement divided by the initial distance between the jaws. Each stress-strain curve was analysed to obtain the

291 mechanical properties of the root (Köhler et al. 1990; Ghestem et al. submitted), in particular
292 its maximal tensile stress (T_{max}) and the ultimate strain at failure (ε_{ult})
293 For the biggest roots, three-point bending tests were performed. Span tests were carried out
294 for each species to check the required sample length:sample mean diameter ratio in order to
295 avoid measuring shear (Isnard et al. 2003). The depth diameter (*d*) and the width diameter (*w*)
296 were measured at three points along the root using a binocular microscope. The axial second
297 moment of inertia (*I*) was calculated using:

298 $$I = (d/2)^3 * (w/2) * (\Pi/4)$$ Eq. 5

299 The bending modulus of elasticity *E* was calculated from the stress-strain curve of 137
300 bending tests as the linear slope at the beginning of the deformation (Rowe & Speck 1996).
301 The bending modulus was not equal to the above-cited tensile modulus of elasticity E_e
302 (Jessome 1971). The flexural rigidity (*EI*) of each sample was calculated as the product *E*I.*
303

304 ## Chemical tests

305 After mechanical testing, roots were dried at 40 °C until constant weight. Nitrogen (N)
306 concentration on 7 (*A. hispidus*) to 77 (*B. championii*) roots per species was determined using
307 an elemental analyser (CHN model EA 1108; Carlo Erba Instruments, Milan, Italy). The
308 concentration of water-soluble sugars was measured on 6 (*A. hispidus*) to 50 (*B. championii*)
309 roots per species, using the Van Soest method (Van Soest 1963), and with a Fibersac 24 fiber
310 analyser (Ankom, Macedon, NJ, USA). The number of analysed roots per species depended
311 on the quantity of available material for each species: collected roots were few and very light
312 for some species (e. g. *A. hispidus)* whereas they were much more numerous and much
313 heavier for other species (e.g. *B. championii).*
314

Statistical analysis

Different statistical tests were used depending on the number and type of factors (Table 4). In the majority of analyses, root diameter was considered a continuous variable. In some analyses, root diameters were separated into two classes: fine]0; 2mm[, and coarse [2mm; +∞[. In such a case, we state “class of diameter”.

Each time parametrical tests are used, the following assumptions were checked: residuals are independent, they have homogeneous variance (homoscedasticity) and they are identically distributed following the normal law $\mathcal{N}(0, \sigma^2)$. If these assumptions are not met, parametric tests were performed on raw data considering the large amount of data in each dataset (>30 raw data in each treatment; Central Limit Theorem; Packard 2011). Data were not log-transformed because of the implied data distortion (Packard 2011). When parametrical tests could not be used, non-parametrical tests were performed. Post-hoc tests used Tukey Honestly Significant Difference (HSD) tests to discriminate among treatments.

Scores for species

In order to propose a classification of the studied species, it was necessary to synthesize clearly. The functional traits of each species were assigned a score depending on their suitability for fixing soil on slopes: for each trait, a score equal to 1 (bad performance), 2 (mean), 3 (good performance) was attributed to each species. A global score was then attributed for each of the three studied properties: (i) ability to colonize steep slope with roots; (ii) mechanical resistance; and (iii) root vivacity (Table 1). To get a more accurate estimation for the resistance in flexion, the score obtained for the maximal tensile strength was crossed with the score obtained for the proportion of fine roots (RAR_f). In the same way, to get a more

accurate estimation for the resistance in flexion, the score obtained for EI was crossed with the score obtained for the proportion of coarse roots (RAR_c).

The rules to synthesize scores were:

Bad performance (score 1) combined with bad performance (1) = bad global performance (1)

Good performance (3) combined with good performance (3) = good global performance (3)

Bad performance (1) combined with good performance (3) = mean global performance (2)

Bad performance (1) combined with mean performance (2) = bad global performance (1)

Good performance (3) combined with mean performance (2) = good global performance (3)

The summary of the global performances for each species will be the basis of the first part of the discussion paragraph (Table 5 and Fig. 14).

Results

Soil characteristics

In situ shear resistance was significantly lower in the hotspot compared to the stable site ($Z_{20,20}$=-3.28, P=0.001; Table 2). In situ resistance to penetration was significantly lower at the hotspot ($Z_{20,20}$= -5.25, P<0.001; Table 2). C was extremely low at both sites, in particular the hotspot (Table 2) whereas Φ was similar (Table 2).

Species abundance

Regardless of site and year, the most abundant species were the two herbaceous species *C. anomala* and *A. hispidus*, followed by the creeping liana *F. tikoua* and then the tree *R. chinensis* ($H_{9,460}$=95.88; P<0.001; Fig. 5). All four species can multiply through clonal reproduction (personal observation). *A. codonocephala* was relatively abundant. *A. americana*, *J. curcas* and *P. stricta* had been planted on the same slope where our fieldsites were located,

but at lower altitude. Nevertheless, results showed that these species had begun to colonize our field sites. *P. stricta* spreads through sexual reproduction, producing numerous and light seeds (personal observation), whereas *A. americana* reproduces largely through the production of underground stems. *J. curcas* reproduces through seeds when adult and had not yet begun to colonize the slope uphill of the plantations. *B. championii* was also not much present (Fig. 5). Certain plant associations were also observed: such as young *P. stricta* with young *A. codonocephala* (Fig. 6).

A. codonocephala, A. hispidus and *C. anomala* produced a significantly higher number of stems m^{-2} at the stable site compared to the unstable hotspot ($H_{2,46}$=6.36; P=0.042; $H_{2,46}$=7.49; P=0.024 and $H_{2,46}$=12.13; P=0.002 respectively). On the contrary, *F. tikoua* possessed a significantly higher number of stems m^{-2} at the unstable hotspot compared to the stable site ($H_{2,46}$=6.54; P=0.038). *B. championii* produced a higher number of stems m^{-2} in July 2010 (very wet period) compared to August 2009 (dryer period; $Z_{22,24}$=-2.46; P=0.013). No other differences were observed between species, with regard to site or year.

Root spread

When standardized by collar diameter (Dc), ISV depended on species ($H_{8,104}$=54.44; P<0.001; Fig. 7). In particular, *B. championii* possessed deeper and wider ISV/Dc compared to other species. *P. stricta*'s root system was also particularly deep. *F. tikoua* and *C. anomala* root systems occupied a very narrow ISV/Dc (Fig. 7). *B. championii, C. anomala* and *P. stricta* occupied a significantly higher ISV/Dc upslope than downslope from the stem (Z_{13}=2.20; P=0.028; Z_{12}=3.06; P=0.002 and Z_{12}=1.80; P=0.007 respectively, Fig. 7). *R. chinensis* exploited a significantly larger ISV/Dc at the unstable hotspot compared to the stable site ($Z_{6,7}$=-1.93; P=0.005, Fig. 7).

388

389 ## Root area ratio

390 RAR was species-dependant ($H_{8,100}$=50.25; P<0.001; Fig. 8), with *A. americana* having a
391 higher RAR than all other species. When *A. americana* was removed from the analysis, the
392 species effect was still significant ($H_{7,86}$=38.78; P<0.001): *F. tikoua, J. curcas, B. championii,*
393 *P. stricta* and *R. chinensis* possessed higher RAR than *A. codonocephala* and moreover than
394 *A. hispidus* and *C. anomala* (Fig. 8). *B. championii, P. stricta* and *R. chinensis* all produced
395 roots deep in the soil profile.

396

397 For all species, RAR decreased significantly with increasing depth except for *A. americana*
398 and *B. championii,* for which RAR at 10-20 cm was not significantly lower than RAR at 0-10
399 cm ($X^2_{14,3}$=14.36; P=0.002 and $X^2_{12,7}$=68.97; P<0.001 respectively, Fig. 8).

400

401 *P. stricta* possessed a significantly higher RAR in the upslope compared to downslope sector
402 (Z_{12}=1.65; P=0.009, Fig. 8). *A. codonocephala* had a higher RAR at the unstable hotspot
403 compared to the stable site ($Z_{4,6}$=2.02; P=0.043). No other significant differences between
404 upslope and downslope sectors or site were found.

405

406 With regard to the RAR of fine and coarse roots, the RAR of coarse roots was significantly
407 greater in *A. americana* (Fig. 9) because we made no distinction between coarse roots and
408 underground stem. The proportion of coarse roots was also higher than the proportion of fine
409 roots for *J. curcas* and *R. chinensis*. *A. codonocephala*, *A. hispidus* and *C. anomala* root
410 systems were composed largely of fine roots, therefore RAR of coarse roots was low (Fig. 9).
411 For *B. championii*, *F. tikoua* and *P. stricta*, RAR of fine and coarse roots were rather similar
412 (Fig. 9).

413

414

415 **Root strength and strain in tension**

416 T_{max} increased with decreasing root diameter in all species except *J. curcas* and *F .tikoua*
417 (increase of T_{max} with increasing root diameter; Fig. 10). T_{max} also differed significantly
418 between species when root diameter was used as a covariate ($Fcov_{9,1105}$=29.85; P<0.001; Fig.
419 10). T_{max} was greater in coarse roots of *F. tikoua* and *P. stricta* but low in *J. curcas* and *R.*
420 *chinensis* (Fig. 10). All other species possessed similar values for the T_{max} of coarse roots (15-
421 20 MPa, Fig. 10). For fine roots, *P. stricta* had the strongest T_{max} (<80 MPa for roots 0.5mm
422 in diameter), followed by *A. codonocephala* and *C. anomala*. *J. curcas* and *R. chinensis*
423 possessed very low T_{max} for fine roots (Fig. 10).

424

425 With regard to depth in the soil, very fine roots (<1mm in diameter) of *B. championii* growing
426 at depth layers > 0.30 m possessed a significantly greater mean T_{max} compared to roots
427 growing in shallower depth layers ($Fcov_{1,192}$=3.91; P<0.001). No other differences were found
428 between species, with regard to mean T_{max} of roots at different depths in the soil.

429

430 For a given root diameter, roots of *A. americana* and *C. anomala* were significantly stronger
431 at the stable site compared to the unstable hotspot ($Fcov_{1,50}$=14.66; P<0.001 and
432 $Fcov_{1,118}$=4.18; P=0.043 respectively). For *P. stricta*, roots coarser than 0.5mm diameter had a
433 higher mean T_{max} at the unstable hotspot compared to the stable site but the tendency was
434 inversed for roots thinner than 0.5mm ($Fcov_{1,286}$=5.21; P=0.023). *R. chinensis* possessed
435 higher mean T_{max} for roots >1.5 mm diameter at the unstable hotspot than at the stable site
436 and again the tendency was inversed for thinner roots ($Fcov_{1,93}$=6.80; P=0.011). No other
437 differences in mean T_{max} between species were found with regard to field sites.

With regard to the season when the roots were harvested for mechanical testing, roots of *A. codonocephala*, *C. anomala* and *P. stricta* were significantly stronger during the dry season (May 2009) compared to the rainy season (July 2010; $F_{1,46}$=26.61; P<0.001; $Fcov_{1,118}$=14.74; P<0.001 and $Fcov_{1,286}$=12.31; P<0.001 respectively). No other significant differences in mean T_{max} were found between species with regard to the season when roots were harvested.

The mechanical behaviour of roots also differed between species with regard to strain. A positive relationship between ε_{ult} and root diameter was significant for *A. codonocephala* (r=0.23, P<0.001) and *P. stricta* only (r=0.48, P<0.001). For all other species, correlations between ε_{ult} and root diameter were not significant. Mean ε_{ult} was significantly different depending on species ($F_{8,1105}$=32.34; P<0.001; Fig. 11). *F. tikoua* had the highest ε_{ult}, followed by *A. hispidus*, *B. championii* and *R. chinensis* (Fig. 11). *A. americana*, *A. codonocephala*, *C. anomala*, *J. curcas* had relatively small mean ε_{ult} with *P. stricta* having the the smallest mean ε_{ult}.

Regardless of diameter, roots of *A. codonocephala* had significantly smaller mean ε_{ult} at depth layers > 0.30m in the soil compared to roots growing at 0 to 0.10m, 0.10 to 0.20m and 0.20 to 0.30m ($Fcov_{4,146}$=3.65; P<0.001). However, in roots at a depth >0.30m in both *P. stricta* and *R. chinensis*, mean ε_{ult} was significantly greater than in shallow roots ($Fcov_{5,286}$=5.64; P<0.001 and $F_{5,91}$=3.93; P=0.003, respectively). No other differences between species with regard to mean ε_{ult} and soil depth were found.

With regard to differences between upslope and downslope sectors and regardless of root diameter, mean ε_{ult} in roots of *P. stricta* were significantly shorter upslope compared to

463 downslope ($Fcov_{1,286}$=5.88; P=0.016). No other differences were found between species with
464 regard to slope direction. Roots of *P. stricta* also possessed a mean ε_{ult} that was significantly
465 smaller at the unstable hotspot compared to the stable site ($Fcov_{1,286}$=6.76; P=0.023) and also
466 significantly smaller during the dry season (May 2009) compared to the rainy season (July
467 2010; $Fcov_{1,286}$=9.75; P=0.002). However, roots of *A. hispidus* possessed significantly smaller
468 mean ε_{ult} in July 2010, compared to the drier month of June 2010; $F_{1,89}$=295.29; P=0.041). No
469 other significant differences in mean ε_{ult} were found between species with regard to the season
470 when roots were harvested.
471

472 ## Resistance in bending

473 Bending stiffness increased with root diameter in species where large and stiff roots were
474 found, i.e. all species except *A. hispidus*, *C. anomala* and *F. tikoua* (Fig. 12). EI differed
475 significantly between species when root diameter was used as a covariate ($Fcov_{6, 128}$=240.41;
476 P<0.001; Fig. 12). Roots which were the most resistant in bending belonged to *A. americana*
477 (coarse roots were underground stems), with maximal values of 400 kN mm², *P. stricta* (300
478 kN mm²), *R. chinensis* and *J. curcas* (both with maximal values around 1.50 kN mm²),
479 followed by *B. championii* (15 kN mm²) and *A. codonocephala* (3 kN mm²).
480

481 The only significant difference with regard to site was found for roots of *P. stricta*, where
482 mean EI was higher at the unstable hotspot compared to the stable site ($Z_{21,5}$= -2.08; P=0.037).
483 Data were probably too few to obtain significant comparisons between root depth in the soil
484 and slope sector.
485

Chemical composition

The quantity of N present in roots depended on species ($F_{8,231}$=33.48; P<0.001, Fig. 13a) and the interaction between species and root diameter ($F_{15,224}$=26.32; P<0.001, Fig; 13a). *A. codonocephala* had the highest quantity of N present in roots, regardless of root diameter (Fig. 13a). The leguminous *P. stricta* also possessed high levels of N in fine roots (Fig. 13a). So did the fine roots of the leguminous *B. championii*, in a lesser exent (Fig. 13a).

With regard to slope sector, all roots of *A. codonocephala* growing downslope contained more N than those growing upslope ($Z_{9,7}$=-2.12; P=0.034). In *J. curcas*, N was significantly higher for roots growing upslope compared to those growing downslope ($Z_{5,5}$=2.30; P=0.021). No other differences in root N between species were found with regard to slope sector.

With regard to site, root N was significantly greater in all roots of *A. americana*, *B. championii*, *P. stricta* and *R. chinensis* growing on the unstable hotspot ($Z_{17,32}$=4.19; P<0.001; $Z_{24,\ 44}$=3.29; P<0.001 and $Z_{29,21}$=3.54; P<0.001; $Z_{5,6}$=2.46; P=0.014 respectively). No other differences in root N between species were found with regard to site.

The quantity of water-soluble sugars in roots depended on species ($F_{8,336}$=8.26; P<0.001, Fig. 13b) and on the interaction between species and root size ($F_{8,333}$=356.88; P<0.001, Fig. 13b). For all species, water-soluble sugars content was significantly lower in fine roots compared to coarse roots, with the lowest concentration found in fine roots of *A. americana* and the highest in coarse roots of the same species. *F. tikoua* and *A. codonocephala* possessed low quantities of water-soluble sugars in both fine and coarse roots. *A. hispidus*, *B. championii*, *P. stricta* and *R. chinensis* all had high quantities of water-soluble sugars (Fig. 13b).

With regard to root depth in the soil, the only significant difference found between species, was that the amount of water-soluble sugars was significantly lower in roots of *A. codonocephala* at a depth 0 to 0.10m and 0.10m to 0.20m compared to those deeper than 0.20m ($H_{3,26}$=9.71; P=0.021).

The slope direction had a significant effect on the amount of water-soluble sugars in roots of *B. championii* only. Upslope roots contained less water-soluble sugars than downslope roots, regardless of depth in the soil ($Z_{21,44}$=-2.19; P=0.028). The only differences between sites were in roots of *P. stricta*, which presented less water-soluble sugars at the stable site compared to the unstable hotspot ($Z_{31,23}$=-3.06; P=0.002). On the contrary, roots of *R. chinensis* possessed more higher water-soluble sugars at stable hotspot than at the unstable site ($Z_{33,38}$=4.21; P<0.001).

Discussion

Differences in functional traits between species and sites

The functional traits of each species were examined with regard to their desirability for fixing soil on slopes (Table 5; Fig. 14). Each species possessed one or several traits which were desirable for improving slope stability, but no one species possessed a suite of traits that were ideal for fixing soil. *P. stricta* and *A. codonocephala* had roots which were mechanically resistant and had good vivacity. Their ability to occupy slope soil with roots was mean (Fig. 14). In the case of *P. stricta*, weak occupation of soil by roots was mainly due to a low number of stems per square meter, which can be quite easily compensated by human action (planting, manuring…) *J. curcas* and *A. americana* had been planted supposedly to counteract

slope instability and erosion processes, as suggested in previous studies (Reubens et al. 2011, Petrone & Preti 2008, Achten et al. 2007), yet we found that, even if their mechanical properties were high, these species were not among the most suitable for reinforcing soil (Fig. 14). *A. hispidus* (herb), *B. championii* (leguminous liana) and *R. chinensis* (tree with vegetative multiplication by roots) did not possess the same root system morphology (Fig. 4), yet they obtained the same global scores: they were poor in mechanical resistance and global root vivacity, and mean in soil occupation by roots. The methodology of classification used in this study allows considering very different species together and estimating their functional performance. Native creeper *F. tikoua* shows a low global performance. But *F. tikoua* also possessed evergreen leaves, thus protecting surface soil from raindrop splash impacts and hence surficial erosion (Norris et al. 2008).

Monsoon season

Several species possessed different properties depending on the season. Among them, *B. championii* did show an increase of stem presence from July 2010 to August 2009, but this might be an effect of progressive colonization of the slope by this species rather than an effect of season. *A. codonocephala*, *C. anomala* and *P. stricta's* root resistance (estimated by an increase of T_{max} for these three species and a decrease of ε_{ult} for *P. stricta*) decreases during wet season. Usually, dry roots are more brittle and thus more fragile (Nick Rowe, pers. comm.) Hathaway and Penny (1975) showed that during winter and wet conditions tensile strength of *Salix* and *Populus* clones is higher. In temperate trees, fine roots which are present during the winter months of temperate species are usually longer-lived and thicker than those present during the summer months, which die before the onset of winter (Mao et al. 2012). It is difficult to explain why these three latter species do not follow the general trend. Therefore, the chemical composition may be different in roots harvested at different times of the year, because of inherent differences in root structure linked to the longevity of the root.

560 The only species with a slight advantage during monsoon season is *A. hispidus*, whose roots
561 deform less in wetter conditions.
562

563 ## Species for slope short-term restoration or long-term protection?

564 All species show significant differences of their root traits whether they grow in stable or in
565 unstable conditions (except obviously *J. curcas* which was not tested on unstable hotspot).
566 Species which show comparative advantages on unstable conditions can be used for slope
567 restoration or short-term protection after a landslide (see Aronson et al. 1993; SER Science
568 and Policy Working Group 2002; Burylo 2010 for definitions of ecological restoration:
569 assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed) to
570 stabilize a slope after a landslide (Fig. 15). This is the case for *F. tikoua* which is more present
571 on unstable conditions, all other properties remaining equal; *P. stricta* and *R. chinensis* which
572 have stronger roots on unstable conditions. Yet, *P. stricta's* have a significantly higher water-
573 solubles content on unstable conditions than on stable conditions, therefore decomposition
574 after root mortality should be faster in these roots. *A. codonocephala* had a higher RAR on
575 unstable conditions. Still, *A. codonocephala* is less present at unstable hotspot, thus human
576 action is needed to enhance colonization. Roots of *B. championii, A. americana, P. stricta* and
577 *R. chinensis* at the hotspot had higher N contents, suggesting that these roots had greater
578 metabolic activity.
579 Species which show comparative advantages on stable conditions should be used for slope
580 long-term protection, in order to prevent from potential future landslides (Fig. 15). This is the
581 case for *A. americana* and *C. anomala* concerning mechanical properties and for *A.*
582 *codonocephala* and *A. hispidus* concerning slope colonization.
583

Where is the most efficient location for species on hotspots?

To reinforce a slope against landslides, roots have to cross the potential shear plane. The potential shear plane of a slope can be circular or parallel to the soil surface (Fig. 15). Therefore, as it is unlikely that any one species can posses an entire suite of traits that are optimal for increasing slope stability, different species can be planted on a slope, at different positions along the slope, to optimise soil reinforcement. For example, species with vertical and strong roots will fix soil better in the middle of the slope whereas plants with more and stronger roots upslope or downslope will better reinforce the top or toe of the slope, respectively (Danjon et al. 2008, Fig. 16). In our study on small areas of soil slippage, or hotspots, the precise location of species is all the more relevant because the depth of the potential shear zone may increase or decrease rapidly from the top to the bottom of the hotspot (Fig. 16). Except for *F. tikoua* and *A. hispidus*, all species had roots which possessed different traits, depending on the depth of the root as well as its orientation with regard to slope direction. *A. americana* and *B. championii* both had a high density of roots deeper in the soil and roots of the latter species were significantly stronger than shallower roots, and deeper roots of *A. codonocephala* had significantly smaller values of strain, therefore these three species are able increase the reinforcement of the potential shear zone in depth. The root system of *C. anomala* occupied a larger soil volume near the soil surface whereas those of *B. championii* and *P. stricta* occupied a greater soil volume deeper in the soil upslope compared to downslope. *P. stricta* had more numerous and stronger roots upslope. The water-soluble sugars content in upslope roots of *B. championii* was lower upslope, therefore, these roots will take a longer time to decay (Craine et al. 2005). These four species will therefore be more efficient for improving slope stability when planted at the top of a hotspot (Fig. 16).

In this study, we demonstrated that it is unlikely that any one species possesses the entire suite of root traits necessary to efficiently stabilise a slope with regard to shallow landslides. We suggest the use of mixtures of species, as well as a targeted spatial use of species in particularly fragile hotspots. Such mixtures have been shown to be more efficient at decreasing soil erodibility with regard to water erosion (Pohl et al. 2009), but to our knowledge, this is the first study whereby an in-depth study of desirable root traits with regard to slope stability has been performed. As this was a short-term study, it is now necessary to project root traits' efficacy over time, especially as the woody species examined were in the immature stage.

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634

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Tables

Table 1

Traits to compare species efficiency to stabilize steep slopes and their abbreviations. Ultimate tensile strain is a trait representing both the mechanical resistance of the roots and the root vivacity.

Plant properties	Functional traits	Abbreviations
High presence of roots in the soil	High number of plant stems per m² of degraded slope, high individual soil volume standardized by the collar diameter of the plant, high root area ratio	Nb stems.m-², ISV/Dc, RAR
High mechanical resistance of roots	High maximal tensile strength crossed with high proportion of fine roots, short ultimate tensile strain, high rigidity in flexion crossed with high proportion of coarse roots	$T_{max,}$ $\varepsilon_{ult,}$ EI
High root vivacity	Short ultimate tensile strain, high root nitrogen content, low water-soluble sugars content	ε_{ult}, N, water-solubles

Table 2

Soil textural, chemical and physical characteristics in horizons A and B at the hotspot and stable site. The number (n) of samples is indicated for each test. Data are means ± standard error.

Soil property	Soil horizon	Stable site	Unstable hotspot
		n=8	n=8
Clay (%)	A	41.70 ± 6.73	49.21 ± 2.66
Silt (%)		44.04 ± 4.46	41.12 ± 4.25
Sand (%)		14.27 ± 1.69	9.68 ± 3.61
Clay (%)	B	47.62 ± 8.52	46.71 ± 11.49
Silt (%)		42.20 ± 6.59	39.03 ± 8.37
Sand (%)		10.18 ± 2.41	14.26 ± 7.34
		n=8	n=8
pH		8.42	8.33
CEC cmol(+).kg^{-1}		51.51	43.81
Organic carbon (g.kg^{-1})	A	12.31	25.8 ± 1.9
	B		28.7 ± 1.4
Total nitrogen (g.kg^{-1})	A	0.91	1.5 ± 0.1
	B		0.7 ± 0.8
		n=7	n=7
Soil water content (%) in August 2009		27 ± 8.23	28 ± 6.62
Soil water content (%) in July 2010	A	18.28 ± 3.73	23.29 ± 8.28
	B	17.48 ± 3.26	15.3 ± 3.50
Soil water content (%) at saturation		60 ± 7.44	70 ± 3.00
Dry bulk density (g.cm^{-3})	A	0.88 ± 0.23	0.78 ± 0.03
	B	1.01 ± 0.18	0.99 ± 0.16
		n=20	n=20
Resistance with manual shear tore vane (kPa)		0.27 ± 0.02	0.17 ± 0.02
Resistance with manual penetrometer (kPa)		3.25 ± 0.20	1.48 ± 0.13
		n=8	n=8
Soil cohesion (kPa)		5.35 ± 1.97	0.49 ± 0.92
Angle of internal friction (°)		20. 21 ± 3.02	26.98 ± 1.41

1 Table 3

2 Shoot characteristics and time of harvest for individuals studied (means ± se)

Species	Family	n	Height of plant crown (cm)	Width of plant crown (cm)	Width of collar diameter Dc (cm)	Months when roots were collected
A. americana	Asparagaceae	14	16.81 ± 20.45	22.91 ± 39.77	0.43 ± 0.56	July 2010 (very wet month)
A. codonocephala	Asteraceae	12	12.74 ± 4.37	22.27 ± 8.45	0.75 ± 0.35	May 2009 (very dry month) and July 2010 (very wet month)
A. hispidus	Poaceae	12	17.25 ± 11.29	15.00 ± 6.15	0.43 ± 0.16	June (wet month) and July 2010 (very wet month)
B. championii	Leguminosae	12	20.82 ± 12.38	27.77 ± 28.20	0.61 ± 0.30	June (wet month) and July 2010 (wet month)
C. anomala	Poaceae	12	11.78 ± 6.92	17.18 ± 6.18	5.41 ± 6.70 (tufts)	May 2009 (very dry month) and June 2010 (wet month)
F. tikoua	Moraceae	11	7.60 ± 3.03	36.38 ± 31.27	0.71 ± 0.33	August 2009 (dry month) and July 2010 (very wet month)
J. curcas	Euphorbiaceae	5	22.80 ± 9.39	15.30 ± 10.77	0.17 ± 0.06	July 2010 (very wet month)
P. stricta	Leguminosae	12	33.75 ± 26.06	22.98 ± 11.32	0.41 ± 0.17	May 2009 (very dry month) and June 2010 (wet month)
R. chinensis	Anacardiaceae	13	16.54 ± 8.73	22.54 ± 11.46	0.50 ± 0.23	August 2009 (dry month), June (wet month) and July 2010 (very dry month)

3

Table 4

Depending on the variables tested, different statistical tests were used. Abbreviations used in the text are also indicated.

Statistical test	Presentation of results and parameters	Analyzed data
Linear correlation between two continuous variables	r=correlation coefficient, $R^2=r^2=$ coeff of determination	$Log(T_{max})$ and ε_{ult} depending on diameter
Anova: parametrical test of analysis of variance	$F_{\text{factor df, errors df}}$ value; P value	N and water-solubles depending on species and classes of diameter
Ancova: parametrical test of analysis of covariance with root diameter as covariable	$Fcov_{\text{factor df, errors df}}$ value; P value	T_{max}, ε_{ult} and EI depending on species; T_{max} and ε_{ult} depending on depth, up/downslope, sites and season
Kruskal-Wallis non parametrical test for independant variables	$H_{\text{n=nb cases, N=nb of observations}}$ value; P value	Number of stems m^{-2}, ISV/Dc and RAR depending on species; EI, N and water-solubles depending on depth
Friedman Anova non parametrical test for dependant variables (>2)	$X^2_{\text{N=nb of observations, factor df}}$ value; P value	RAR depending on depth
Mann-Whitney U non parametrical test for two independant variables	$Z_{\text{nb of valid observations in one case, nb of valid observations in the other case}}$ value; P value	In situ soil resistance, in situ soil penetration, Number of stems m^{-2}, ISV/Dc, RAR, EI, N and water-solubles depending on sites; Number of stems m^{-2}, ISV/Dc and RAR depending on seasons
Wilcoxon matched pairs non parametrical test for two dependant variables	$Z_{\text{nb of valid pairs}}$ value; P value	ISV/Dc, RAR, EI, N and water-solubles depending on up/downslope

Table 5

Multi-criteria table summarizing performances of each species: traits and related functions. 1/2/3: bad/mean/good performance.

Functional traits and **Related functions**	*A. ame.*	*A. codo.*	*A. hisp.*	*B. cham.*	*C. ano.*	*F. tik.*	*J. curc.*	*P. stric.*	*R. chin.*
High presence on hotspots (High number stems m^{-2})	1	2	3	1	3	2	1	1	2
High propagation of roots (High ISV/Dc)	2	2	2	3	1	1	2	3	2
High root density (High RAR)	3	2	1	2	1	2	2	2	2
Capacity of soil occupation	2	2	2	2	1	1	1	2	2
High resistance in tension (High fine roots RAR*high T_{max})	1*2=1	3*3=3	3*2=3	2*2=2	3*3=3	2*2=2	1*1=1	2*3=3	1*1=1
High resistance in bending (high coarse roots RAR* high EI)	3*3=3	1*2=1	1*1=1	2*2=2	1*1=1	2*1=1	3*3=3	2*3=3	3*3=3
Short deformation (Short ε_{ult})	3	3	1	1	3	1	3	3	1
Mechanical resistance	3	3	1	1	3	1	3	3	1
High metabolism (High N)	1	3	1	2	1	1	1	3	2
High longevity (Low water-solubles)	2	3	1	1	3	3	3	1	1
Short deformation (Short ε_{ult})	2	2	2	2	2	1	2	3	2
Root vivacity	1	3	1	1	2	1	2	3	1

Figure legends

Figure 1

Ombrothermical diagram from Liuku meteorological station situated 30 km South from the field site (source: Meteorological Bureau of Yunnan Province). Arrows show the months when roots were collected

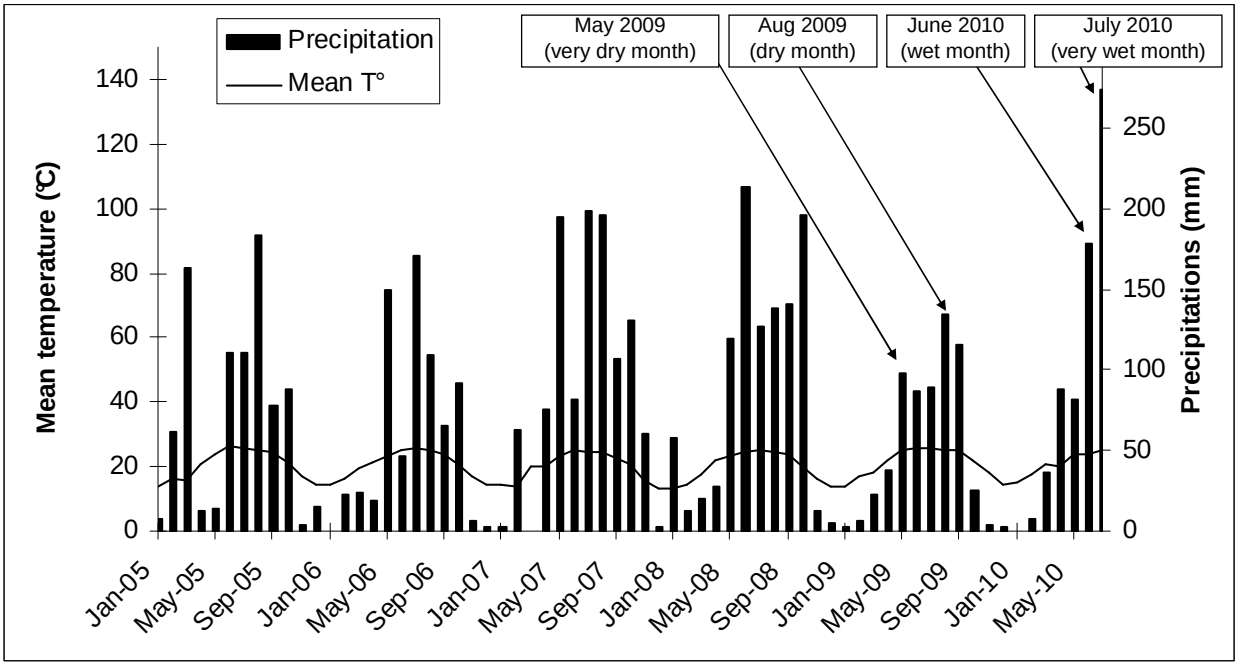
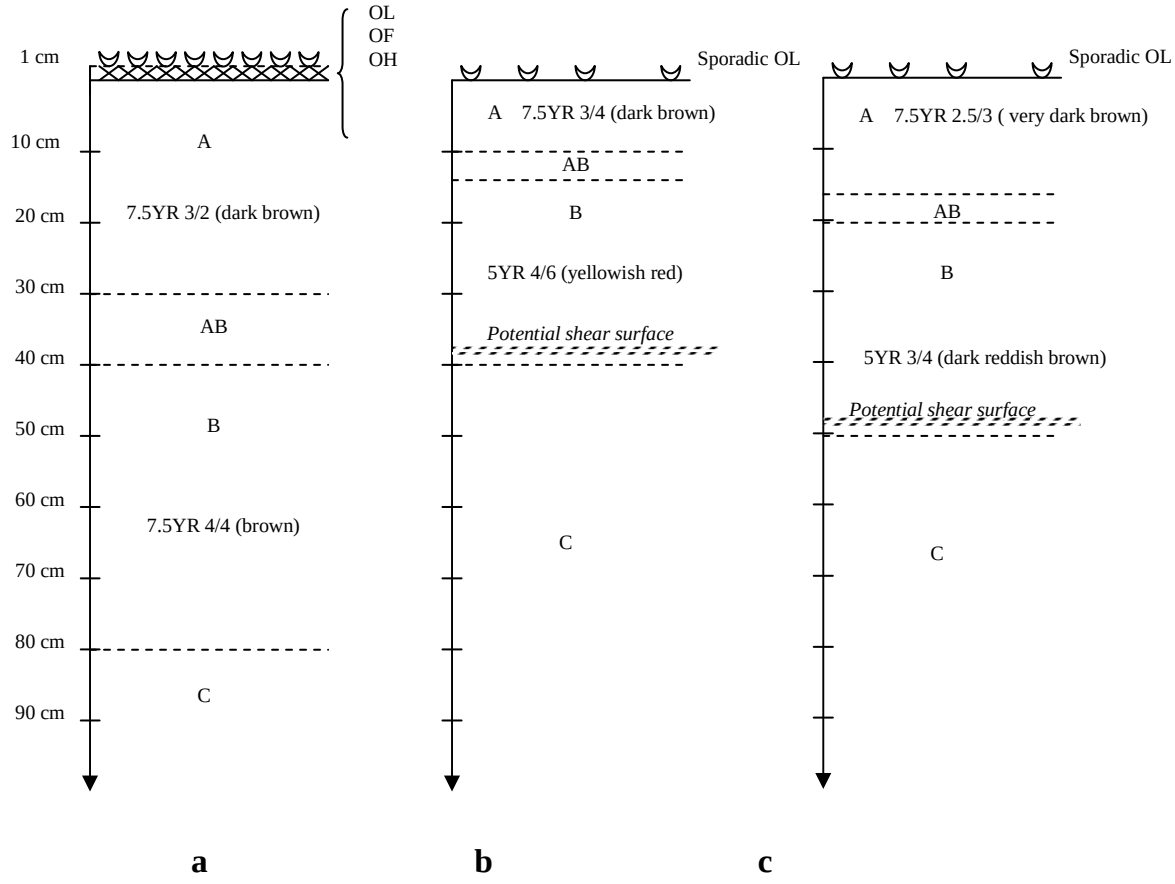


Figure 2

Soil horizons at a) a site with no previous evidence of landslides or erosion; b) the stable site where a shallow landslide had occurred eight years previously and c) the hotspot. Colours were identified using a Munsell colour chart (Munsell 1947). OL: fresh litter, OF: fermenting litter, OH: litter with humic substances and well-transformed organic matter, A: organico-mineral layer, AB: mixture between A and B, B: layer of bedrock alteration, pieces of bedrock are visible, C: bedrock, mineral layer (Legros 2000; Baize and Girard 1995)



1 Figure 3

2 Pictures of the nine selected species

3

Figure 4

Root systems of the nine studied species and the depth they reached. *A. americana*'s root system was composed by an underground stem from which emerged thin roots; *A. hispidus*'s root system was composed by few thin roots emerging from the plant collar; *A. artemisia* possessed a root system with long lateral roots diving into depth as they grew old; *B. championii* possessed long and deep roots, able to change direction and densely branched; C. anomala showed a tuft and shallow root system; *F. tikoua*'s roots emerged from creeping stems; *J. curcas* and *P. stricta* both possessed tap root systems, yet *P. stricta*'s was deeper and more densely branched; *R. chinensis* had a sprouting root system composed by long, deep and scarcely branched roots.

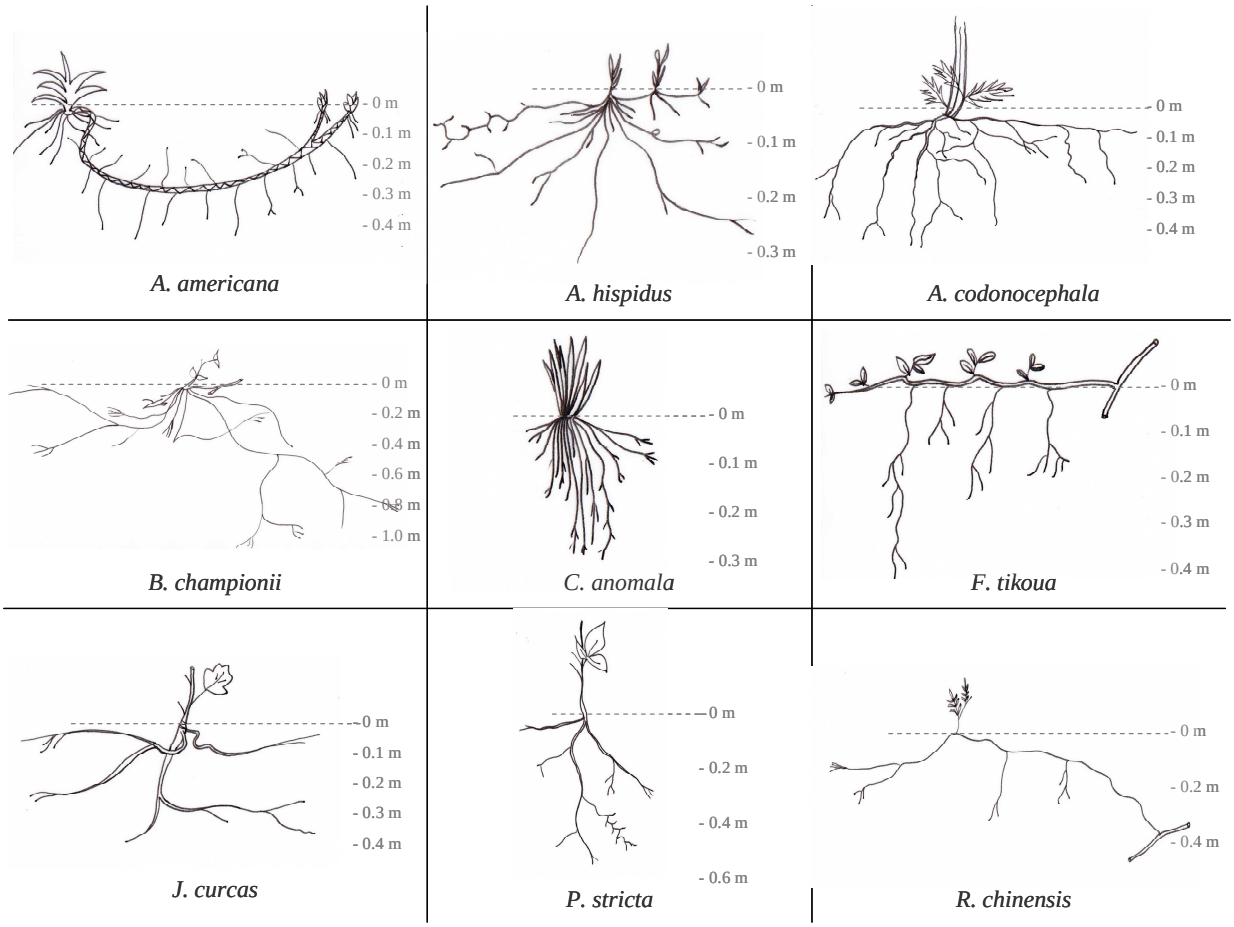


Figure 5

Presence of species on hotspots for each year. “Others”: *Bidens pilosa* Linn., *Celosia argentea* L., *Elsholtzia winitiana* Craib, *Indigofera* sp., *Malvastrum coromandelianum*, *Convolvulus arvensis*, *Solanum verbascifolium* Linn.

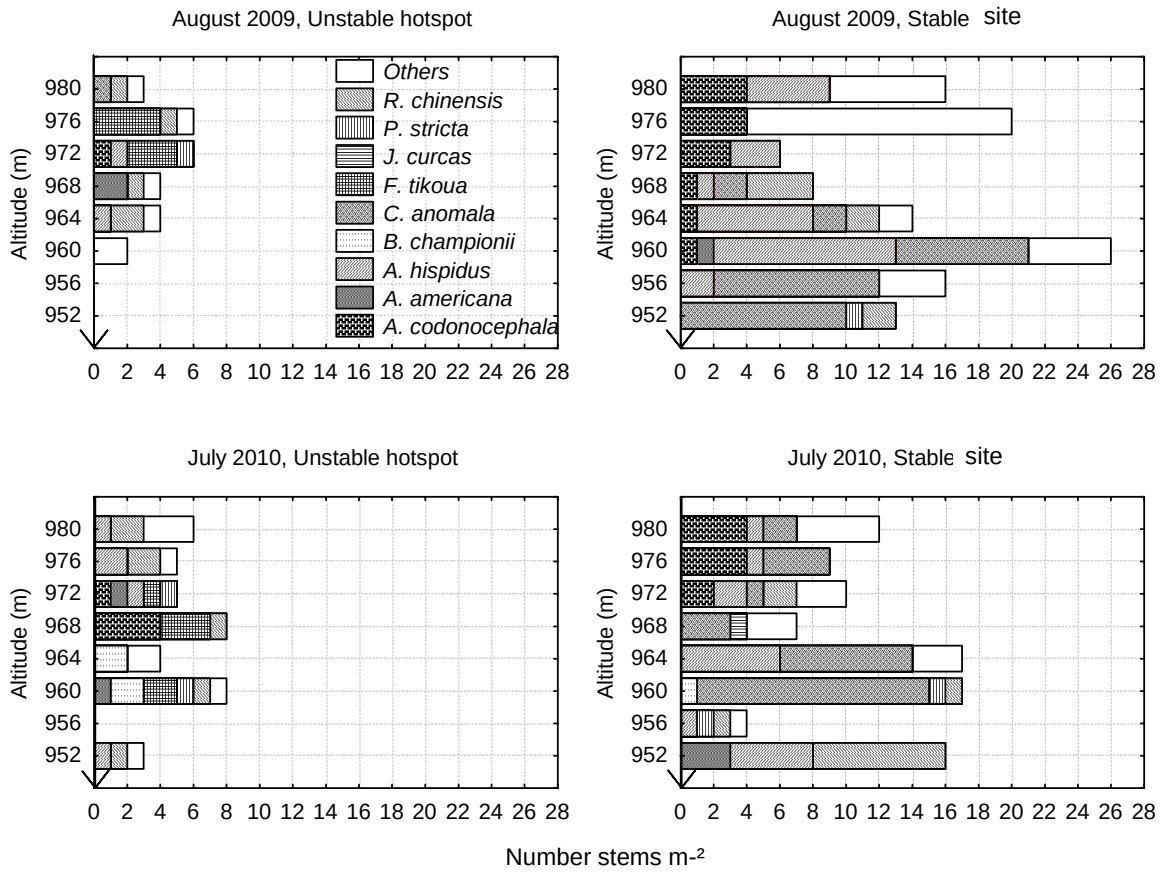
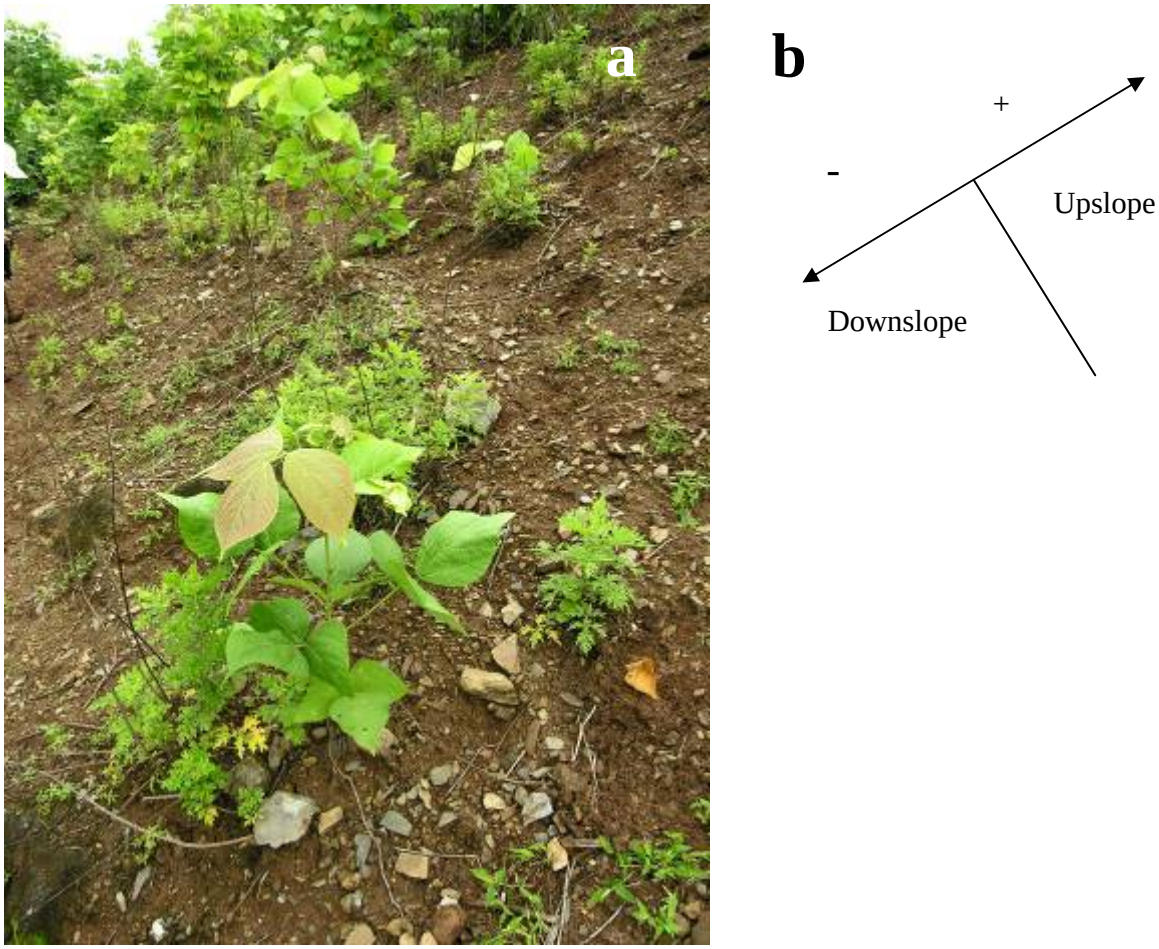


Figure 6

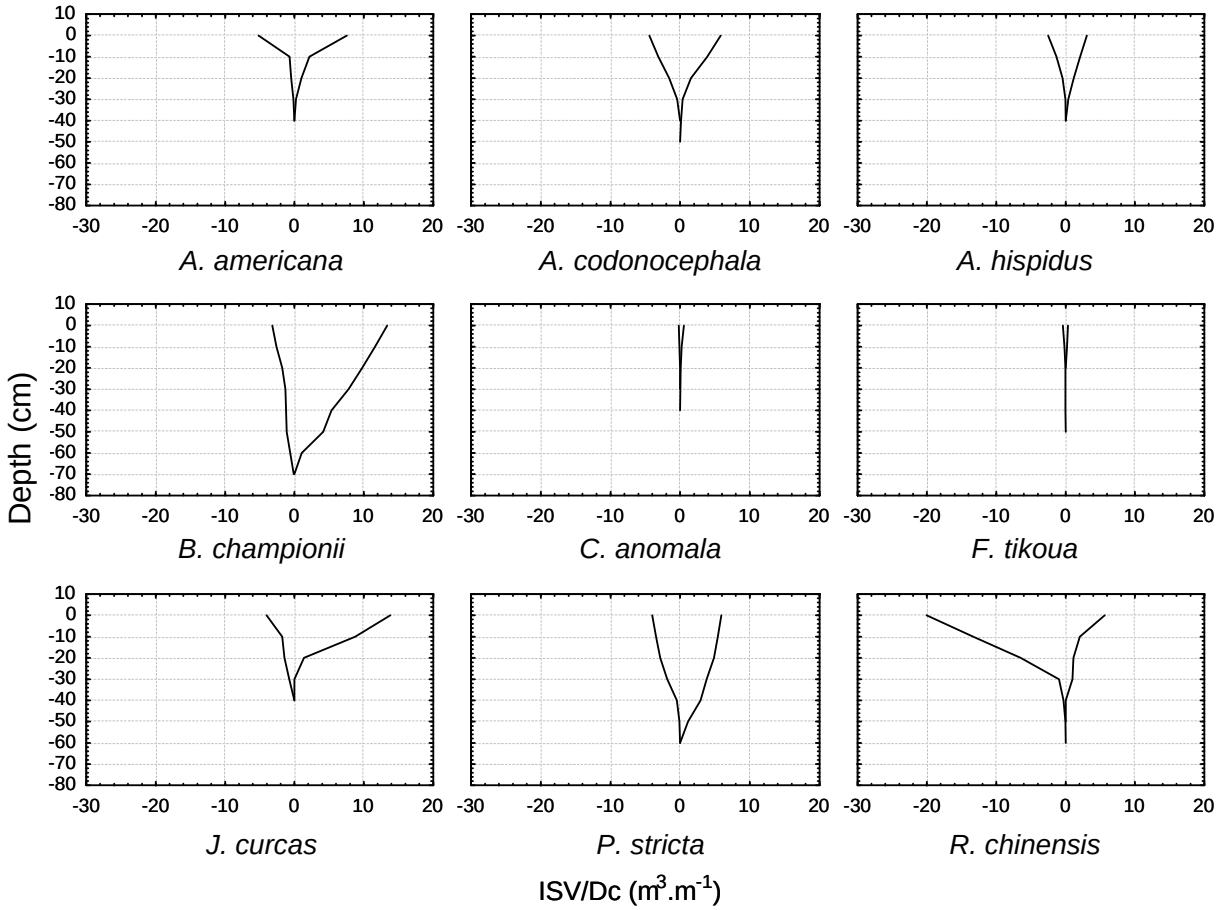
a) *A. codonocephala* - *P. stricta* association; b) drawing of up/downslope limit



1 Figure 7

2 Mean individual soil volume standardized by collar diameter (ISV/Dc). Negative values of

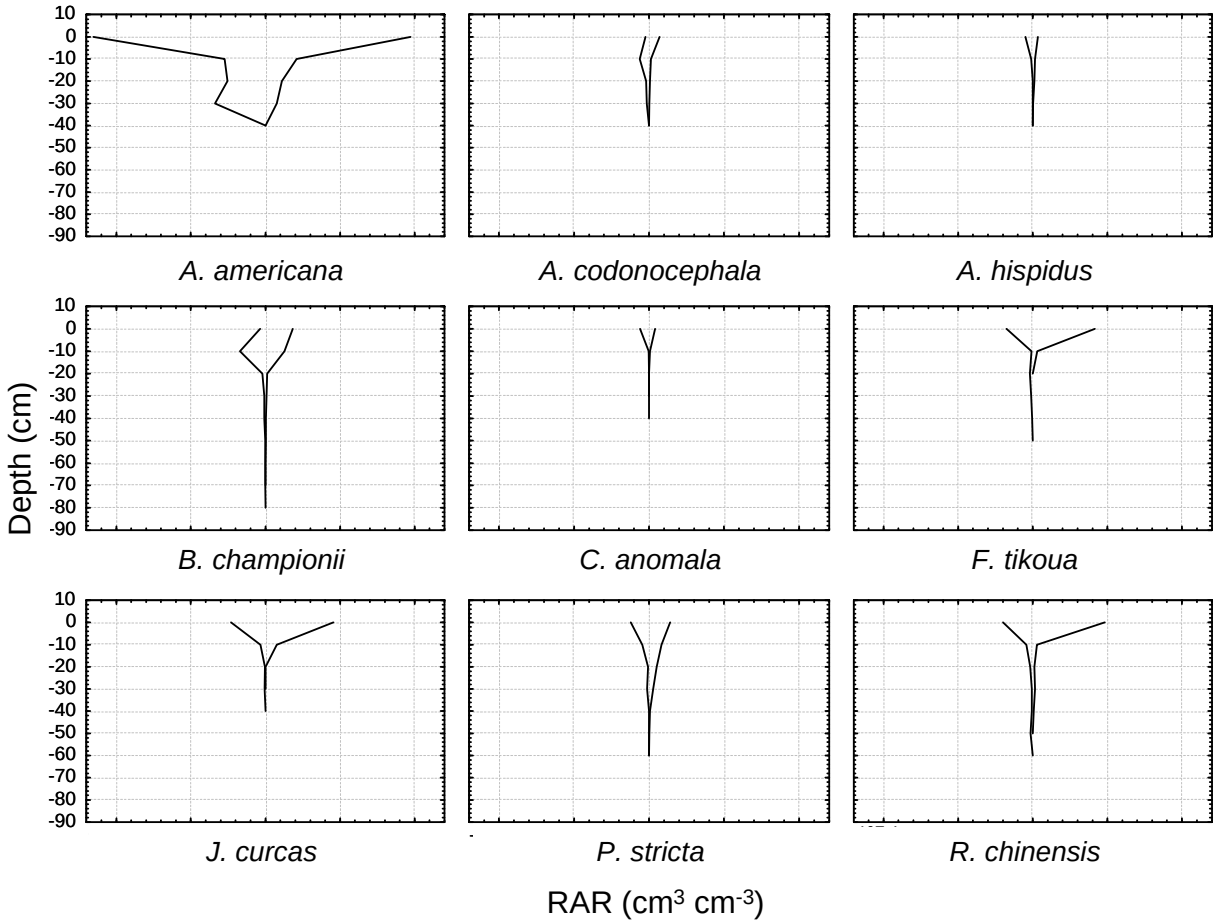
3 ISV/Dc represent downslope orientation



4

1 Figure 8

2 Root area ratio (RAR) of all species. Negative values of RAR represent downslope orientation



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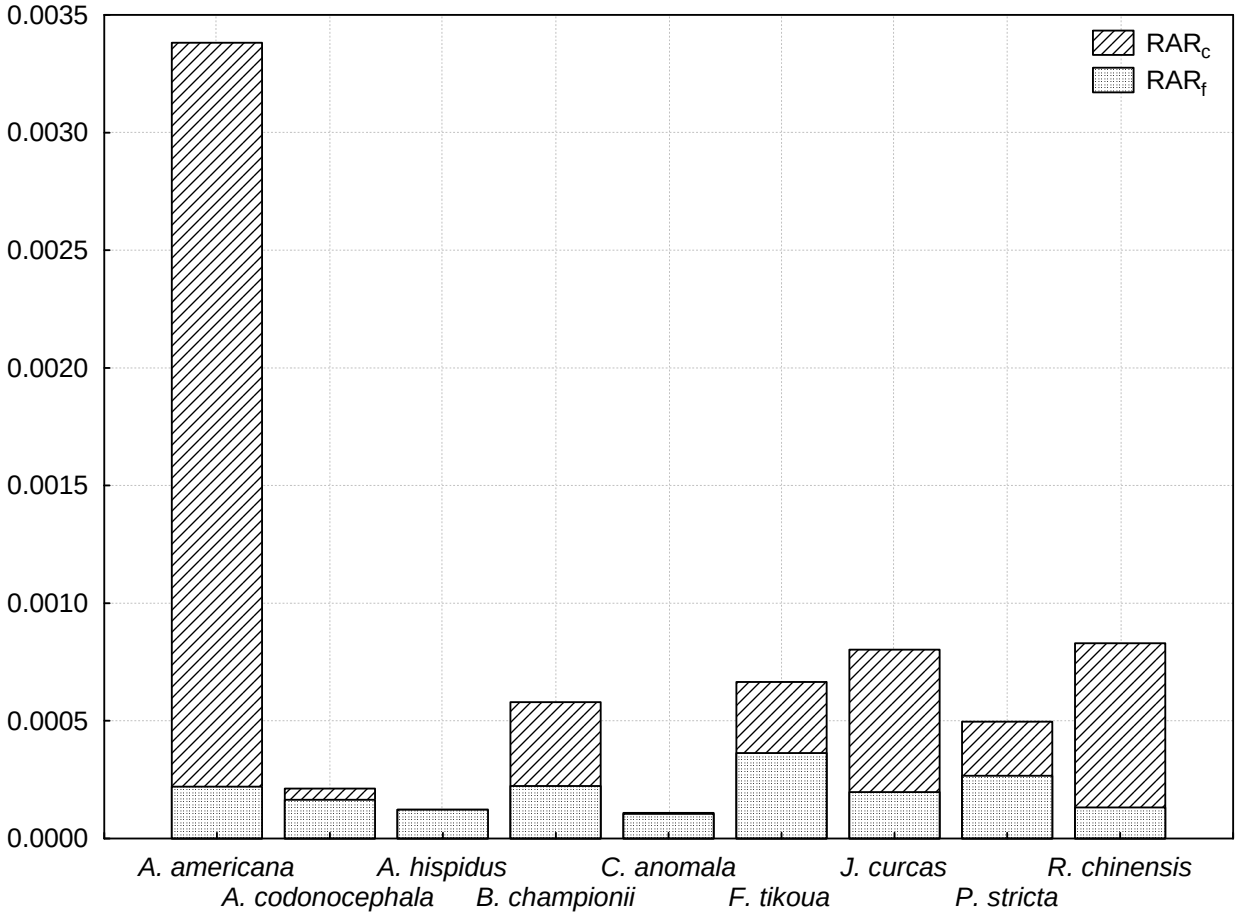
1 Figure 9

2 Coarse and fine roots area ratio (RAR)



3

Figure 10

Tensile stress at failure (T_{max}) for diameters from 0 to 2 mm. Logarithmic scales. Fitting curves: $T_{max} = \alpha * D^{-\beta}$, equations are presented on the graphs with determination coefficient, parameters in brackets are non significant

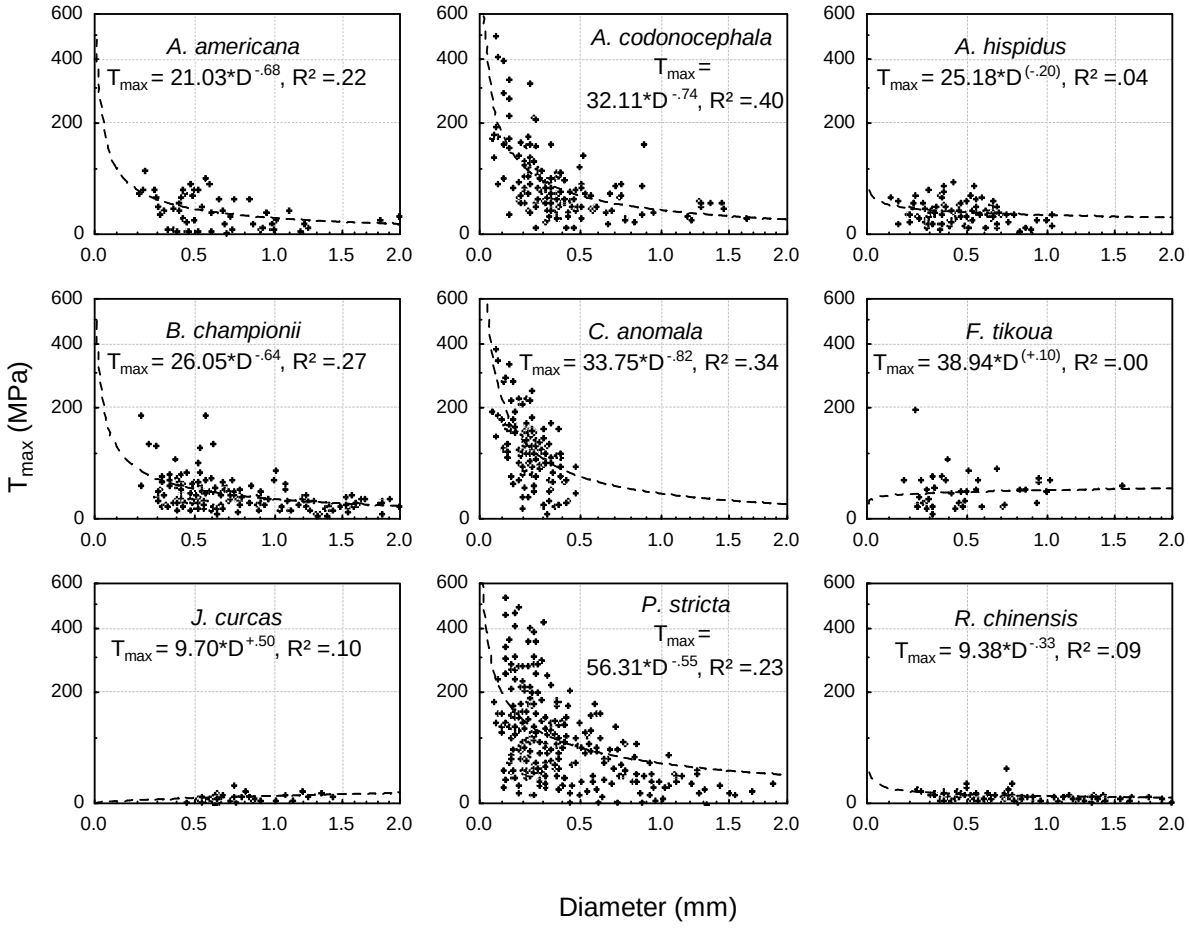


Figure 11

Ultimate strain at failure per species. Vertical bars denote 0.95 confidence intervals, letters indicate post-hoc differences

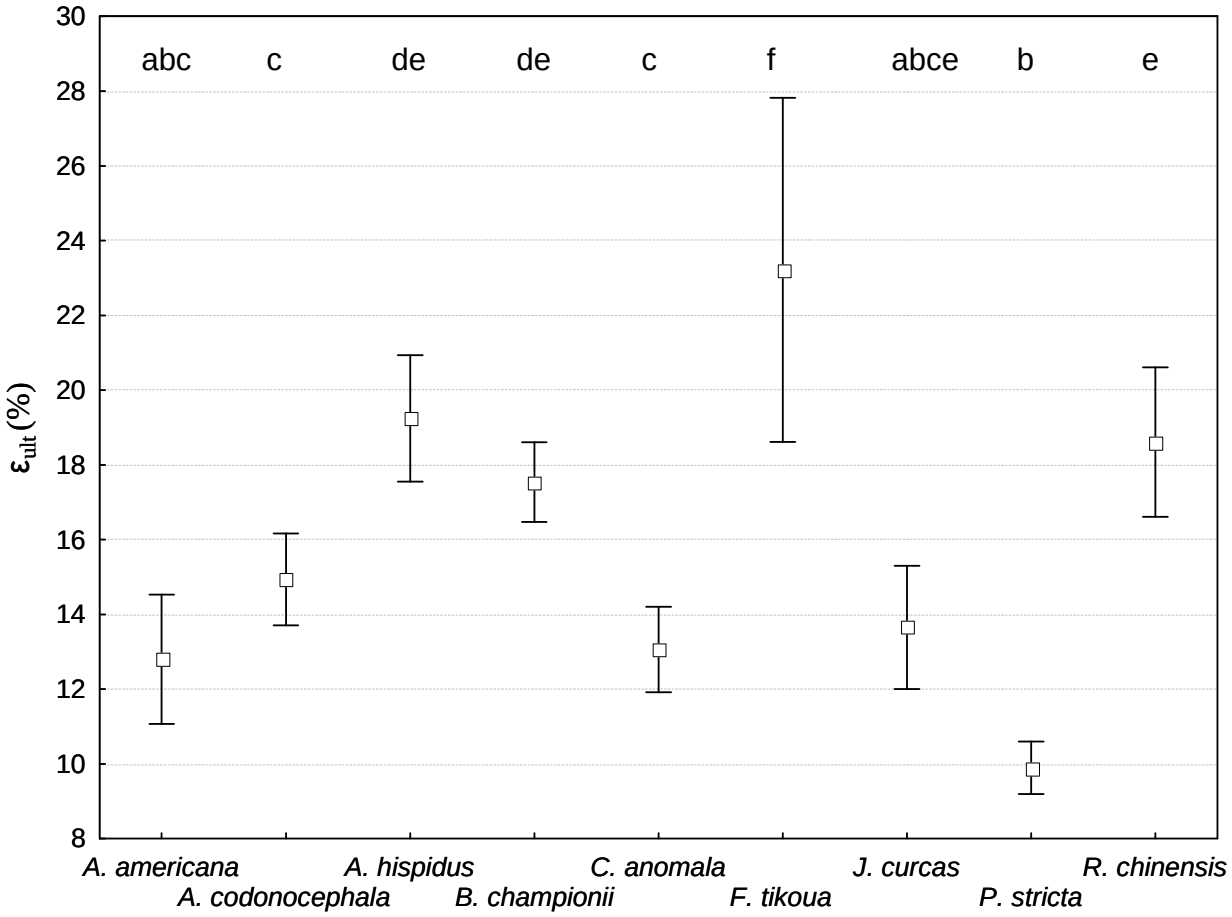


Figure 12

Rigidity in flexion in function of root mean diameter for each species. Root mean diameter is the mean of depth and width diameters for each root. Note that scales are not similar between graphs

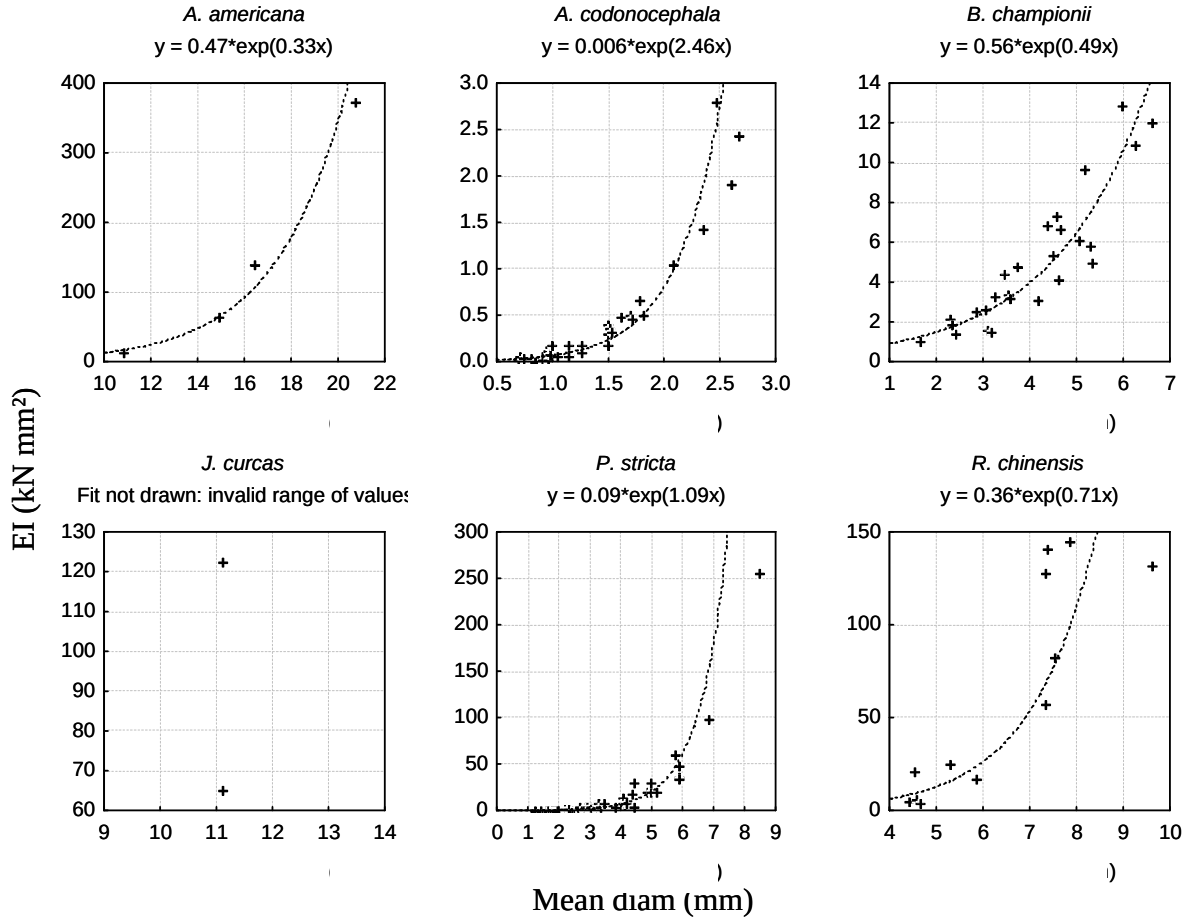
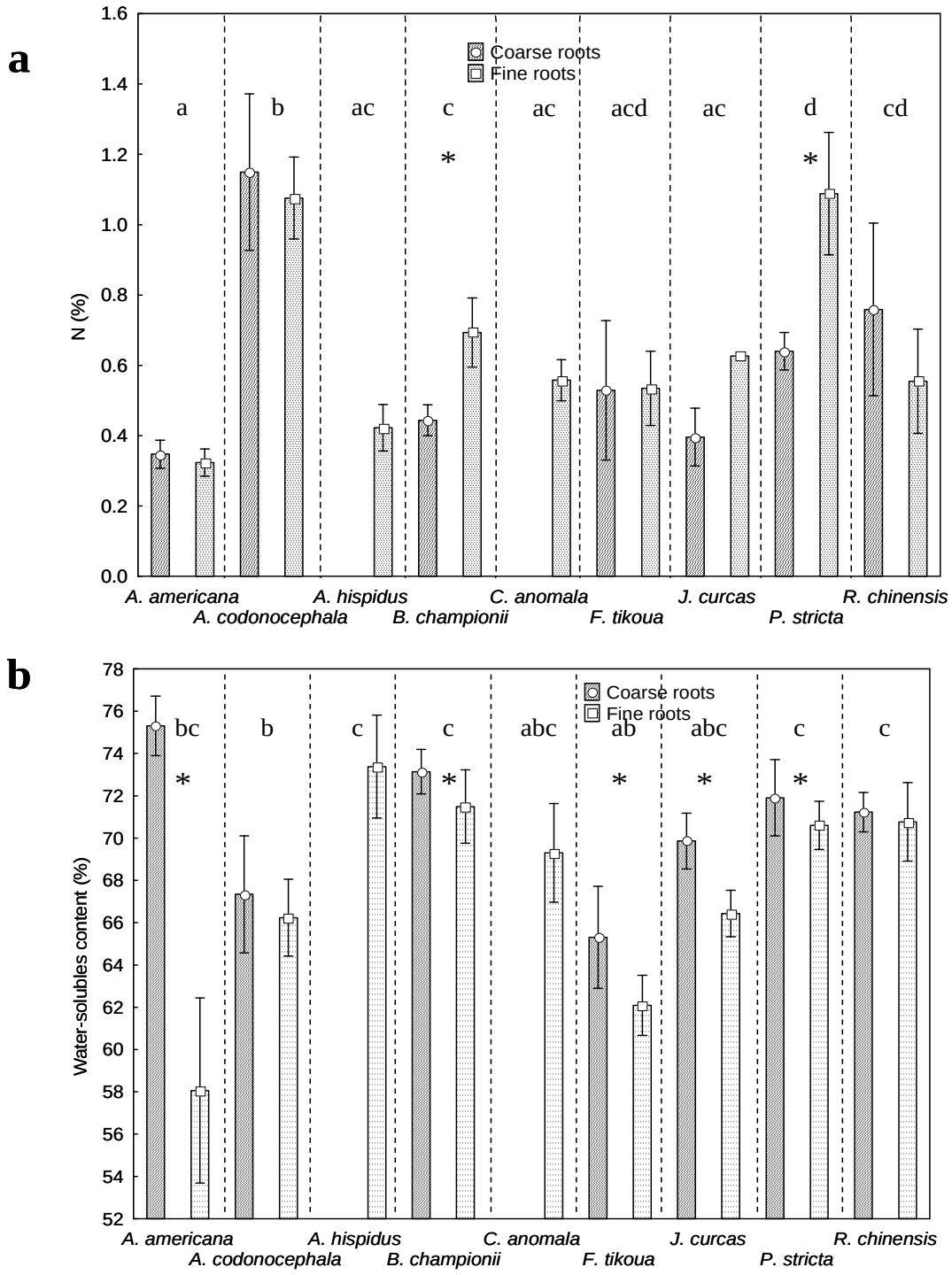


Figure 13

a) Nitrogen and b) water-soluble sugars concentrations in coarse and fine roots for each species. Similar letters denote species with no significant difference. Stars denote significant difference between coarse and fine roots. □ Mean I Mean±0.95 Conf. Interval



1 Figure 14

2 Summary of species performance according to soil occupation, root mechanical resistance and

3 root vivacity

4

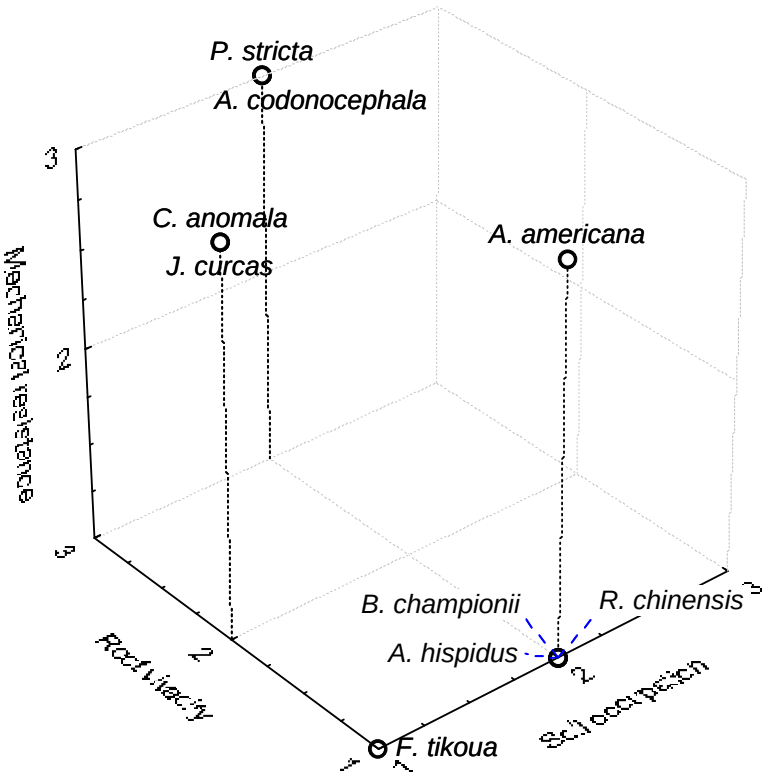


Figure 15

Species for slope short-term restoration and species for slope long-term protection

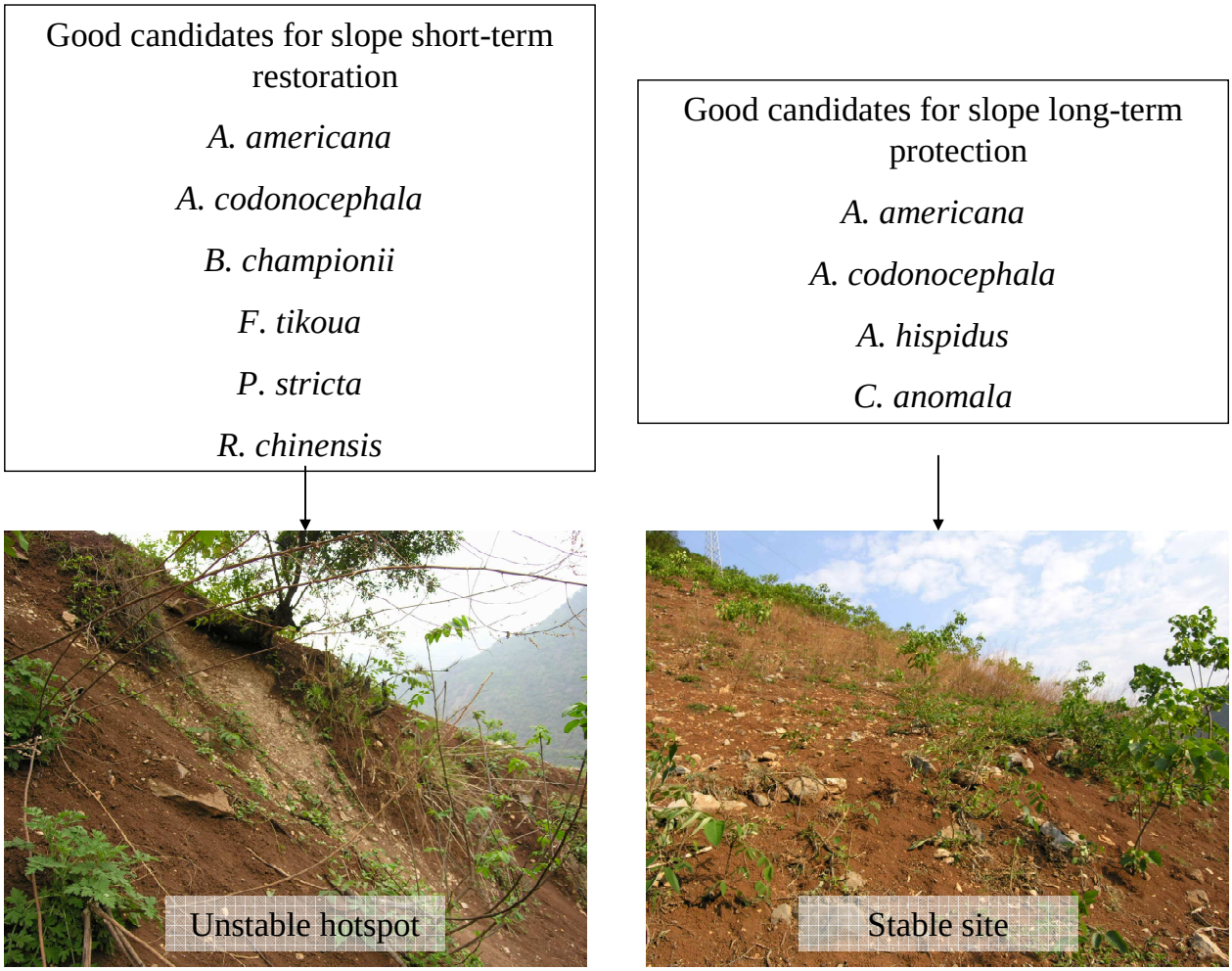
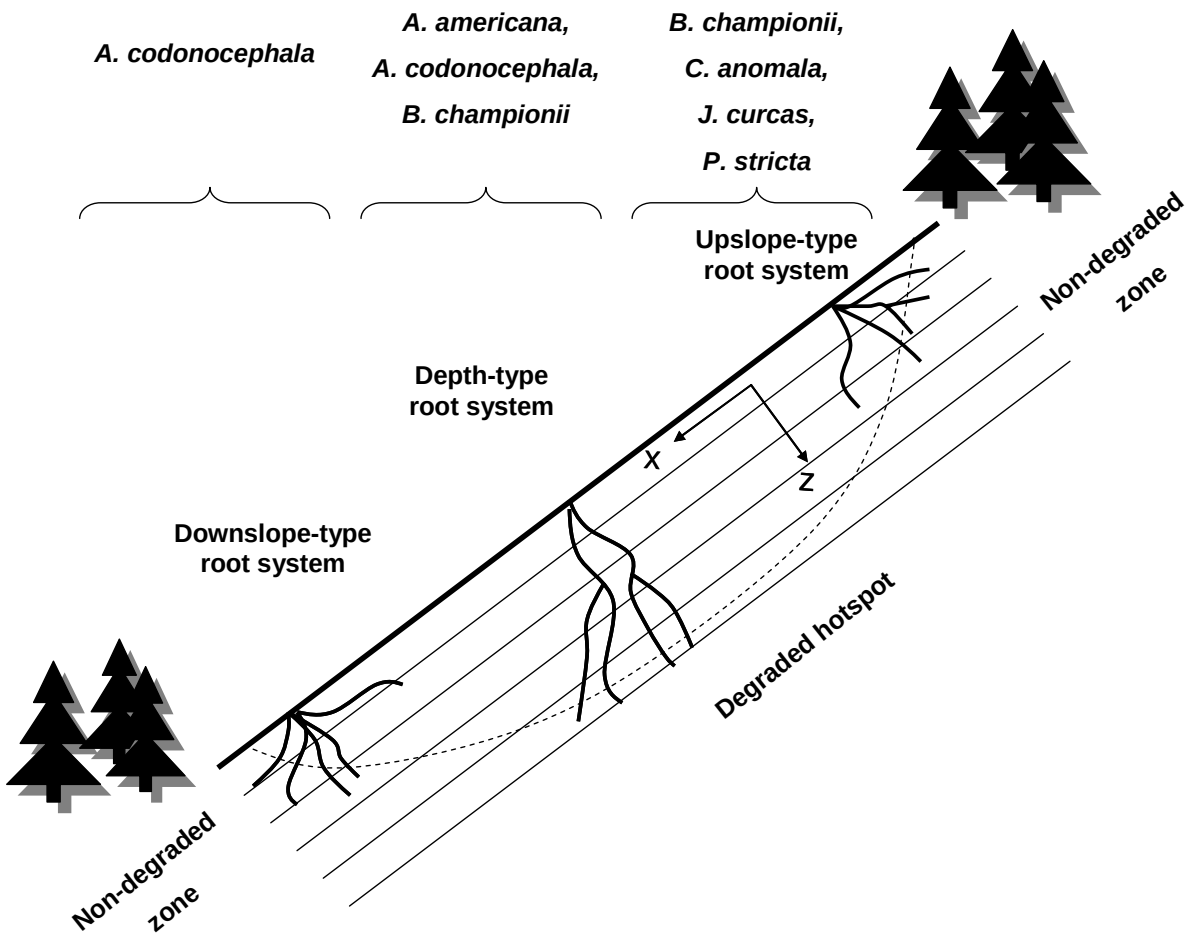


Figure 16

On small degraded slopes (hotspots), root system composition plays an important role: roots growing upslope from the stem will have more chance to cross the potential shear zone if the plant grows at the top of the slope. Thus root systems with desirable traits upslope of the stem will act more efficiently if they are located at the top of the slope, whereas the inverse is applicable for downslope roots. Root systems with desirable traits at depth will act more efficiently in the middle of the hotspot. ---- Potential shear plane



Appendix

Species ecological and ethnobotanical traits.

In brackets: number of the reference in litterature, “obs”: trait deduced from our own observations *in situ* or from dialogues with local inhabitants, light grey cells: good properties, dark grey cells: bad properties.

		Necessary properties		Additionnal properties										TOTAL	
Latin	**Family**	**Present on landslides**	**Not invasive nor adventice nor parasite**	**Perennial**	**Good rooting system *a priori***	**Native of South-East Asia**	**Creeping, sprouting, liana**	**Used for medicine (humans or animals)**	**Used for food**	**Used as forage, fertilizer**	**Used for timber wood**	**Used for power (wood, seed oil…)**	**Used for handcraft (incense, rope…)**	**TOTAL Necessary properties**	**TOTAL Positive properties**
***Ficus tikoua* Bureau**	Moraceae	obs	obs	obs	obs	(43)	obs		(44)				obs	2	6
***Pueraria stricta* Kurz.**	Fabaceae	obs	obs	obs	obs	(72)	obs	(72)		obs				2	6
***Bauhinia championii* Benth.**	Fabaceae	obs	obs	(9)	obs	(9)	obs						obs	2	5
***Jatropha curcas* Linn.**	Euphorbiaceae	(48)	obs	(48)	obs	(48)		(48)		(48)	(48)	(48)	(48)	2	5
Rhus chinensis	Anacardiaceae	obs	obs	(65)		(65)	obs	(65)	obs					2	5
Arthraxon hispidus	Poaceae	obs	obs			(83)	obs			obs				2	3
Chloris anomala	Poaceae	obs	obs			(81)				obs				2	1
Agava americana	Agavacae	obs		(84)		(84)	obs	(84)	(84)			(84)	(84)	1	6
Artemisia codonocephala	Asteraceae	obs		(7)	obs	(6)		(4)	(7)	(7)			(7)	1	6
Coriaria nepalensis Wall.	Coriariaceae		(24)	(24)	obs	(24)		(25)	(25)					1	6
Ficus semicordata	Moraceae		(41)	(41)	obs	(41)		(40)	(40)		(40)	(40)		1	6
Pinus yunnanensis Franch.	Pinaceae		(57)	(57)	(57)	(57)	(obs)				(57)	(57)		1	5
Celosia argentea L.	Amaranthaceae		obs	(20)		(20)		(21)	(19)	(22)				1	3
Pilea plataniflora C. H. Wright	Urticaceae		obs		obs	(56)		(56)						1	3
Inula cappa (Buch.-Ham.) DC.	Compositae	(46)				(46)		(47)						1	2
Viburnum sp.	Caprifoliaceae		obs	obs			obs							1	2
Toxicodendron succedaneum	Anacardiaceae			(73)		(73)		(73)	(73)				(73)	0	4
Pyracantha fortuneana	Rosaceae			(62)	obs	(62)		(62)	(62)		(62)	(62)		0	7
Buddleja officinalis Maxim.	Buddlejaceae			(15)	obs	(15)		(15)	(15)				(15)	0	6
Dodonaea viscosa (L.) Jacq.	Sapindaceae			(28)	obs	(31)		(29)			(32)	(33)	(28)	0	6
Pistacia weinmannifolia	Anacardiaceae			(58)	obs	(58)		(58)			obs	obs		0	6
Ricinus communis L.	Euphorbiaceae			(66)		(65)		(66)	(65)	(66)	(66)	(66)		0	5
Solanum verbascifolium Linn.	Solanaceae			obs	obs	(71)		(71)					(71)	0	5
Achyranthes aspera Linn.	Amaranthaceae			(3)	obs	(1)		(1)		(2)				0	4
Barleria cristata Linn.	Acanthaceae			(8)	obs	(5)		(5)						0	4
Bidens pilosa Linn.	Compositae			(11)		(12)		(11)	(11)	(12)				0	4
Cipadessa cinerascens (Pell.) Hand.-Mazz.	Meliaceae			obs	obs	(23)		(23)						0	4
Pseuderanthemum graciliflorum (Nees) Ridley	Acanthaceae			obs	obs	(59)		(59)						0	4
Senecio scandens	Compositae			(67)		(68)	obs	(68)						0	4
Chelonopsis abbreviata	Lamiaceae			(80)	obs	(80)								0	3
Lagerstroemia sp.	Lythraceae			(49)		(49)		(49)						0	3
Smilax sp.	Smilacaceae					(70)	obs	(70)						0	3
Trema angustifolia (Planch.) Bl.	Ulmaceae			(74)		(74)							(74)	0	3
Desmodium sinuatum Bl.	Fabaceae				obs	(27)								0	2
Fagopyrum tataricum	Plygonaceae			(39)	obs	(39)			(39)	(39)				0	2
Pueraria peduncularis Grah.	Fabaceae					(61)		(61)						0	2
Cotoneaster hebephyllus Diels	Rosaceae			(26)										0	1
Elsholtzia winitiana Craib	Lamiaceae							(34)						0	1
Phlomis sp.	Lamiaceae							(54)						0	1
	Verbenaceae				obs									0	1
Vernicia fordii	Euphorbiaceae		(79)	(78)	obs	(78)		(78)	(78)	(78)	(78)	(78)	(78)	rejected	9
Castanopsis delavayi	Fagaceae	(18)	obs	(17)	obs	(16)			(16)		(17)	(17)	(17)	rejected	7
Phyllanthus emblica L.	Euphorbiaceae	obs	(55)	(55)	(55)	(55)		(55)	(55)	(55)	(55)		(55)	rejected	7
Broussonetia papyrifera	Moraceae		(13)	(13)	obs	(14)		(14)					(13)	rejected	5
Pueraria lobata	Fabaceae		(60)	(60)		(60)	(60)	(60)	(60)	(60)				rejected	5
Urena lobata Linn.	Malvaceae		(77)		obs	(75)		(75)	(77)				(76)	rejected	5
Paederia foetida (L.)	Rubiaceae		(53)	(53)		(53)	(53)	(53)						rejected	4
Quercus acutissima Carr.	Fagaceae	(63)		(63)	obs	(63)	(obs)				obs	obs		rejected	4
Quercus aliena var. acuteserrata	Fagaceae	obs		(64)	obs	(64)	(obs)				obs	obs		rejected	4
Eupatorium odoratum	Compositae	obs	(36)	(36)	obs	(36)	(36)	(37)		(38)				rejected	3
Indigofera sp.	Fabaceae	obs				(45)		(45)		(45)			(45)	rejected	3
Malvastrum coromandelianum	Malvaceae		(51)		(51)	(51)		(52)						rejected	2
Sigesbeckia orientalis	Compositae		(69)	(21)	obs	(21)		(21)						rejected	2
Eupatorium adenophorum Spreng.	Compositae	obs	(35)	(35)	obs	(35)								rejected	1
Loranthus delavayi Van Tiegh.	Loranthaceae		(50)	obs	obs									rejected	1

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Using vegetation to stabilise steep slopes in Southern China: root biomechanics as a factor in the choice of species

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Abstract

In order to identify appropriate species to rehabilitate degraded slopes after landslides in Southern China, we measured two parameters important for fixing soil: root architecture and root tensile strength *(T_r)*. We studied three pioneer species with different growth forms: two native species: *Artemisia lavandulaefolia* (Asteraceae, flowering herb) and *Chloris anomala* (Poaceae, herb), and one planted species: *Pueraria stricta* Kurz. (Fabaceae, shrub).We compared root systems on slopes where a shallow landslide had just occurred and on slopes where the landslide had been stabilized by vegetation. T_r was significantly different between species and with regard to slope type (stable/unstable). *A. lavandulaefolia* had the lowest T_r on stable slopes, but strength was significantly increased on unstable slopes, whereas *P. stricta* and *C. anomala* had lowest T_r on unstable compared to stable slopes. Therefore, with regard to T_r , *A. lavandulaefolia* appeared to be the most appropriate species to stabilize slopes. Results from the root architectural analysis suggested that a combination of the three species would be an optimal ecological combination to increase soil cohesion at all soil depths.

Introduction

In China, a country where two-thirds of the land is made up of hills and mountains, erosion and landslides are the result of deforestation, bad farming practice and over-exploitation of resources in the last 50 years [1][2][3]. China currently feeds 20% of the world population and possesses 7% of the world's croplands [4]. China is also an area with high seismic activity, causing many secondary landslides. The 2008 Wenchuan earthquake, resulted in 80,000 casualties with 20 000 caused by associated geohazards, and by the end of 2008 slopes in the area were not stabilized [5][6]. A major new problem to be faced is the building of roads linking villages to towns [7]. A survey along Nujiang Valley, Yunnan, showed that soil loss rates due to road building represent at least 80% of the total soil loss, and were over 600 times greater than the highest currently recorded in the USA [8]. China has therefore to combine sustainable land management with crop production and rural infrastructure development on sloping land.

Within such a context, mitigation strategies need to focus on target areas of a slope, concentrating on the most fragile zones (degradation hotspots). Recently proposed as a useful technique for restoring eroded land, the management of degradation hotspots [9][10] appears to be one of the most economically viable methods for rehabilitating steep slopes on a large scale. To improve hotspot management, the local ecology needs to be taken into account before a choice of species is made e.g. ethnobotanical knowledge should be used to identify the needs of local farmers and villagers, so that species can provide an income to the local community [11].

Vegetation has long been recognized as a factor useful for increasing the shear resistance of soil on an unstable slope [12]. To better understand how root systems occupy soil over time and space, and especially how root systems cross the potential shear surface of a slope, a landslide engineer needs to

take into account the three-dimensional (3D) root architecture and mechanical properties of any given species. Information on how species grow should be considered, especially during the early stages of growth, as soil conditions strongly affect root growth in the first weeks after germination [13].

The presence of plant roots crossing the potential shear surface results in an increase in soil cohesion through a reinforcing effect which usually augments superficial slope stability. The root – soil reinforcement model developed by Wu [14], and elaborated upon by Waldron [15], is widely used to estimate the additional cohesion taking into account the presence of roots in the soil [16] [17] [18]. This model states that the additional cohesion due to the presence of roots can be estimated as follows

$$C_r = 1.2 * T_r * RAR \qquad (1)$$

where T_r is the average tensile strength of roots and *RAR* is the Root Area Ratio. In the literature, it is often reported that T_r decreases when root diameter *d* increases: fine roots are more resistant in tension than thicker roots [19][20].

In order to better estimate the efficiency of native species in stabilizing slopes, we studied root architecture and measured root tensile strength of three pioneer species on steep slopes in Southern China. So as to estimate their capacity of adaptive growth on slopes where erosive soil slippage was still underway, we selected two adjacent degradation hotspots: one stabilised by vegetation and one unstable. These hotspots were located near a high-biodiversity zone, including more than 25 identified species, which plays the role of a reservoir for colonisation of degradation hotspots. We chose species growing on degradation hotspots at the beginning of the rainy season, when slopes are more prone to landslides. Among the studied species, were two naturally-grown species, *Artemisia lavandulaefolia* (Asteraceae, flowering herb) and *Chloris anomala* (Poaceae, herb), and one planted species, *Pueraria stricta* Kurz. (Fabaceae, shrub).

Material and methods

Our study site is located in Southern China, in Yunnan province, 20 km east of the border with Myanmar (N26°01'60", E098°50'60"). In this area, the river Salween flows from North to South, strictly parallel to the Mekong and the Yangtze. Due to its topographic, climatic and geologic diversity (the Salween river bed follows a major seismic fault resulting from the Indo-Eurasian collision), as well as its location, (this valley was a north-south corridor for species migration especially during glaciation periods). This area is classified as a UNESCO World Heritage site since 2003. Over 6,000 plant species exist, among which more than 300 medicinal plants can be found (http://whc.unesco.org/fr/list/1083).

Altitudes range from 800 m to more than 3,000 m and slope angles can be >50°. This part of China is under the influence of the Indian monsoon, and described as a "warm-dry climate", which is a combination between subtropical and alpine climates. Annual mean temperature (from 1961 to 2002) is 15.2°C, and mean annual precipitation is 1200 mm, the majority of which falls between May and October. The major soil type is a ferrallitic red clay soil, with many mineral coloured spots, e.g. iron and manganese. Except on degradation hotspots, soil and humus thickness are not limiting factors: being 0.2–2.0 m and 0-0.02 cm, respectively. Severe and numerous landslides occur during the monsoon season (May-October), and the slip surface of these landslides has been estimated at a mean depth of 0.5 m. We defined two hotspots of land type: L1 and L2, L1 being an active landslide, and L2 as stable, as natural regeneration and planted shrubs have been allowed to grow undisturbed for 8 years (*Table 1*). Only *C. anomala* was grazed slightly by cows at L2.

Hotspot	Area	A.S.L.	Slope	Orientation	Sliding cause	Sliding date	Bedrock depth	Shear resistance Mean ± $CI_{95\%}$[1]
L1 unstable	20mx30m	1099m	50-60°	300°	rain and gravity	Still sliding	30 cm	0.17±0.03 kg/m²
L2 stable	100mx200m	949m	35-45°		-	± 10 yrs ago	20 cm	0.27±0.03 kg/m²

Table 1: Description of the two hotspots L1 and L2. [1]Shear resistance was measured on 20 points on each landslide, with a Shear Vane (Sols-mesures 14.10). A Mann-Withney Test showed that the shear resistance is significantly different on L1 and L2 ($p<0.05$). A.S.L. is altitude above sea level.

Ten root systems of young individuals of each species were hand-excavated: six growing on L1 and four growing on L2 (*Table 2*). Excavations were carried out with extreme caution and without damaging the roots. Heights and widths of the plants are given, but cannot be used to determine an individual's age. As is often the case in tropical and sub-tropical climates, winter is not severe enough to arrest secondary growth and there is no clear annual ring formation in the stems.

Root system width and depth was measured for each plant and a general architectural description given. Tensile testing was successfully carried out on 1287 root samples, using a portable machine (In-Spec 2200 BT, Instron Corporation, www.instron.com) equipped with a force transducer (max. capacity 250 N, accuracy 0.25%). The length of each sample was at least 30 times its central diameter [21]. Crosshead speed was kept constant at 1.0 $mm.min^{-1}$ and both force and speed were measured constantly via Instron Series IX software during each test. We measured the force required to cause failure in tension of each root. In order to avoid slippage of roots out of the clamps, the clamps where chosen according the diameter of the root. Tests were considered successful only when specimens failed approximately in the middle third of the root. Tensile stress was calculated as the maximal force required to cause failure in the root, divided by the root cross-sectional area (CSA) at the point of breakage.

	n	Min.–Max. height of plant crown (cm)	Min.-Max. width of plant crown (cm)	Min.-Max. root depth (cm)	Min.-Max. distance of the longest root to the stem (cm)	Min.-Max. root diameter (mm) (**no. tests**)	Ethnobotanical uses
Artemisia lavandulaefolia							
L1	6	7.3-20.3	18.4-36.4	18.5-45.0	38.0-51.8	0.01-3.31 (**300**)	Human and cattle medicine.
L2	4	4.6-17.0	13.4-24.0	24.0-34.0	34.7-61.0	0.02-1.5 (**149**)	
Pueraria stricta							
L1	6	15.0-117.0	5.3-31.0	30.0-54.0	25.4-97.0	0.02-4.56 (**296**)	Planted by government for slope stabilisation.
L2	4	15.5-34.0	14.3-32.5	34.0-49.0	11.0-123.0	0.05-4.88 (**176**)	Fixes nitrogen. Cattle forage and shade.
Chloris anomala							
L1	6	6.5-16.5	13.3-20.1	13.8-28.2	23.5-31.7	0.04-0.56 (**205**)	Cattle forage.
L2	4	3.9-12.7	5.5-27.6	11.0-37.0	19.5-63.5	0.01-0.51 (**161**)	

Table 2: Size of aerial and underground parts of plants (depth: perpendicular to the soil surface).

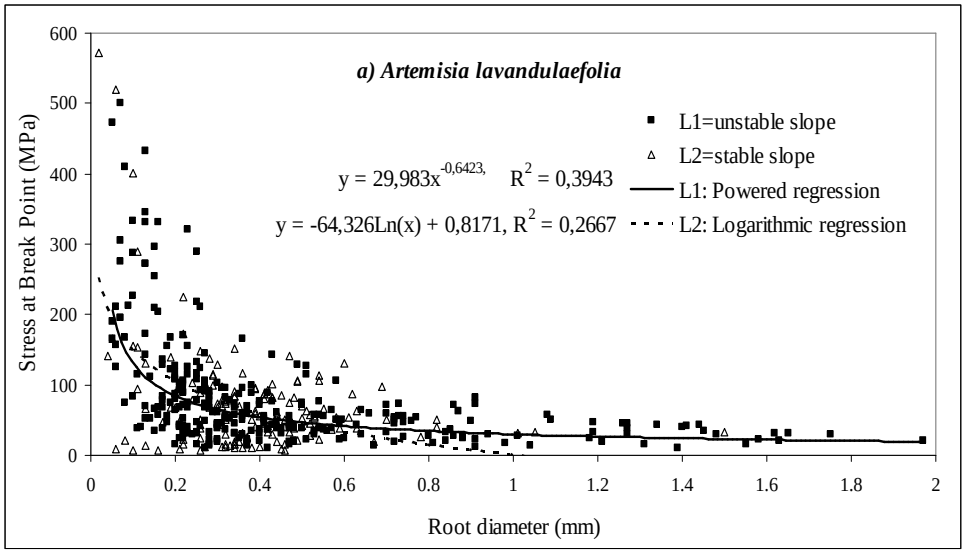
For each species and on each hotspot, we drew the best regression curve between tensile stresses and root diameters. To determine whether or not differences exist in root tensile stress between species and between hotspots, analysis of covariance (ANCOVA) was carried out with tensile stress as the dependent variable, species and hotspot type as the factors, and root diameter as the covariate. When data were not normally distributed ($p<0.05$) and did not show the same deviation standard, a logarithmic transformation was performed. Noticeably, in this study, parametric tests were also performed on raw data considering the large amount of data in each dataset (Central Limit Theorem).

Results

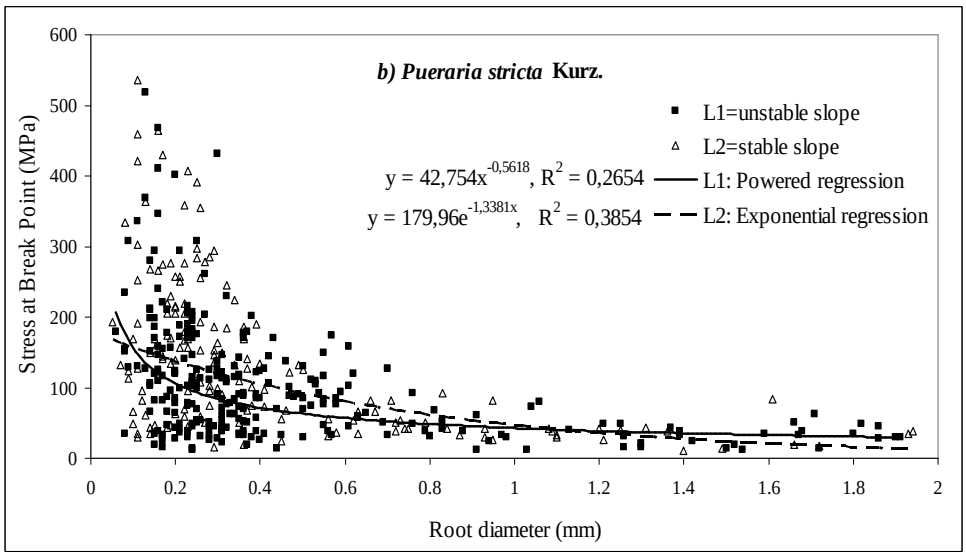
Root architecture

During the first stages of growth, *A. lavandulaefolia* had long lateral subhorizontal roots (macrorhizae). In general, one taproot grew deeply and long lateral roots grew obliquely at an angle of approximately 45°. Macrorhizae extremities branched into very fine roots. Small fibrous roots (brachyrhizae) were dispersed in clusters along the long branches *(Table 2, Fig 1a). P. stricta* possessed one differentiated taproot with long subhorizontal branches. The taproot was often long and tortuous. Few root hairs were observed and fibrous brachyrizhae were confined in a zone around the

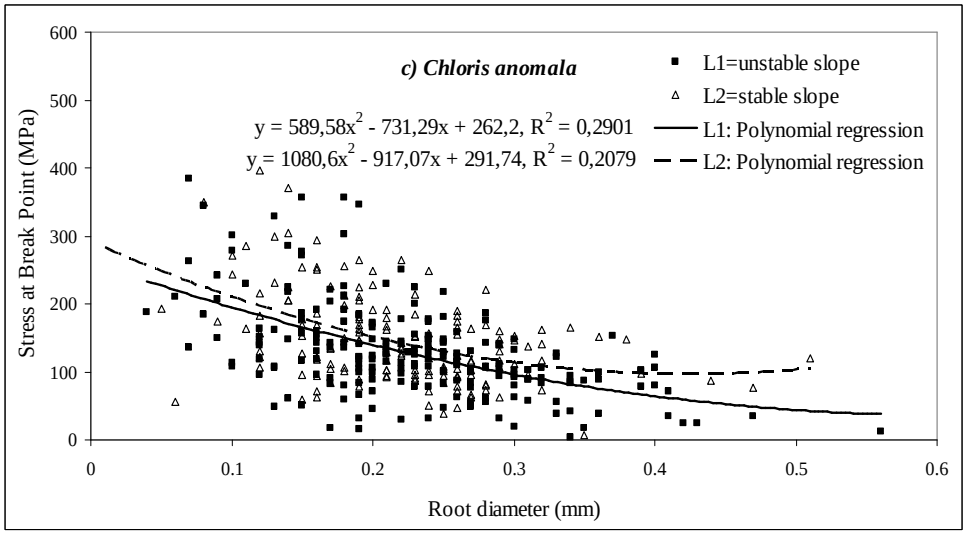
collar and at the extremities of long branches (*Table 2, Fig. 1b*). *C. anomala* possessed root systems with fine and short roots. Each plant had a small number of roots, but as individuals were clustered into tufts, a mat of roots existed under the soil surface. Individuals were able to develop a layered root system, allowing roots to emerge from the stem above the soil surface *(Table 2, Fig. 1c).*

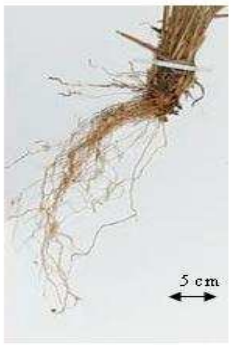


a) Artemisia lavandulaefolia: *long lateral roots*



b) Pueraria stricta*: taproot system*





c) Chloris anomala: *fine fibrous roots*

Fig.1: Relationships between stress at rupture (MPa) and root diameter (mm), and the best-fit regression curve (p<0.005) .a) Artemisia, *b)* Pueraria, *c)* Chloris, *and their respective root systems.*

Root tensile strength *(Fig 1 and 2)*

A. lavandulaefolia, P. stricta Kurz.and *C. anomala* had similar mean values for tensile strength, especially on the unstable hotspot, but variability in data dispersion was high (*Fig 2*). Tensile strengths were comparable or even higher than those observed on trees in other studies [18] [20]. *A. lavandulaefolia* had the highest minimal mean and *C. anomala* the maximal mean at the stable hotspot. *A. lavandulaefolia* possessed the lowest standard deviation (SD) at the stable hotspot, and the highest SD at the unstable hotspot. For all species, tensile strength decreased with increasing root diameter (*Fig 1*), following different regression models.

Tensile strength was significantly different on the two types of hotspots for each species ($F_{2, 1276}$ = 8.09, p<0.001, ANCOVA, *Fig.2*). *A. lavandulaefolia* had a much higher tensile strength on the unstable hotspot, whereas *P. stricta* and *C. anomala* possessed higher tensile strengths on the stable slope.

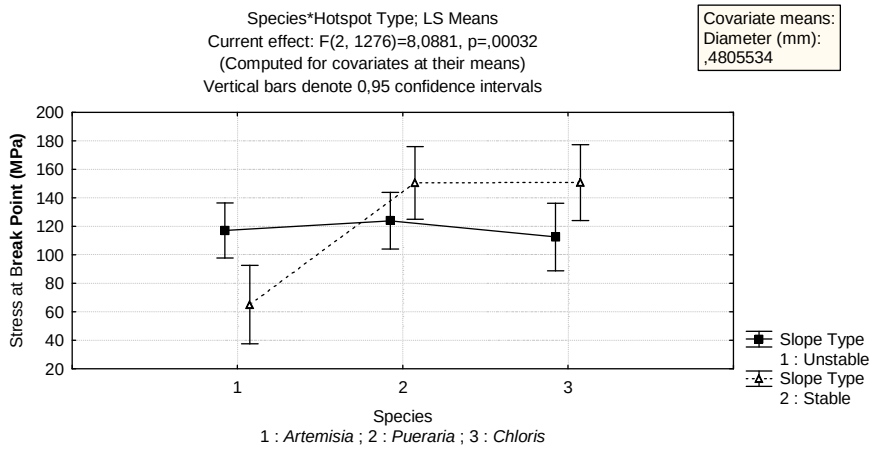


*Fig.2: Analysis of covariance with tensile strength as dependent variable, species and hotspot types as factors and diameter as covariate. The effect of Species*Hotspot type is significant.*

Discussion

With regard to root architecture, the ability of *C. anomala* to produce roots up the stem and above the soil surface is useful on slopes, when soil slippage can leave downhill roots exposed. By growing layers of roots uphill, the plant can stay anchored, although at an expense of producing deeper roots. This fast-growing herb is complementary to slower growing shrubs and trees, especially on unstable erosion hotspots where a shallow reinforcement of soil is required. *P. stricta* possessed a deeply growing taproot, fixing the soil through a thicker zone and thus crossing deeper potential shear surfaces. These three species, observed together on the slopes, seem to be an optimized ecological combination for soil stabilisation.

Considering mechanical properties of the roots, we suggest that *A. lavandulaefolia* is the species best adapted to soil slippage, as tensile strength increased when plants grew on unstable soil, contrary to *P. stricta* and *C. anomala*. Interestingly, *P. stricta* has been chosen by government authorities to plant on unstable slopes, even though root tensile strength decreases. The values we obtained for tensile strength in fine roots were extremely high, but similar values have been observed for fine roots of woody species [22]. It would be of great interest to carry out more testing of such small diameter roots, and to determine why tensile strength values may be so high in certain roots. We will also carry out a similar study on secondary succession species, and determine which mechanical and architectural traits are most useful at maintaining soil and preventing landslides on steep slopes.

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Effects of vegetation type on soil resistance to erosion: Relationship between aggregate stability and shear strength

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ABSTRACT

Soil water erosion and shallow landslides depend on aggregate stability and soil shear strength. We investigated the effect of vegetation on both soil aggregate stability and shear strength (through direct shear tests) in former croplands converted to vegetated erosion protection areas within the context of China's sloping land conversion programme. Four treatments were analysed in plots comprised of (i) 4 year old crop trees, *Vernicia fordii*, where understory vegetation was removed; (ii) *V. fordii* and the dominant understory species *Artemisia codonocephala*; (iii) only *A. codonocephala* and (iv) no vegetation. Soil samples were taken at depths of 0–5 cm and 45–50 cm. Root length density (RLD) in five diameter classes was measured, soil organic carbon (SOC), hot water extractable carbon (HWEC), texture and Fe and Al oxides were also measured. We found that mean weight diameter after slow wetting (MWD_{SW}) in the A-horizon, was significantly greater (0.94–1.01 mm) when *A. codonocephala* was present compared to plots without *A. codonocephala* (0.57–0.59 mm). SOC and RLD in the smallest diameter class (<0.5 mm), were the variables which best explained variability in MWD_{SW}. A significant positive linear relationship existed between MWD_{SW} and soil cohesion but not with internal angle of friction. As herbaceous vegetation was more efficient than trees in improving aggregate stability, this result suggests that the mechanisms involved include modifications of the cohesive forces between soil particles adjacent to plant roots and located in the enriched in SOC rhizosphere, thus also affecting shear strength of the corresponding soil volume. Thus, vegetation stabilised soil under different hierarchical levels of aggregate organisation, i.e. intra- and inter-aggregate. Our results have implications for the efficacy of techniques used in land conversion programs dedicated to control of soil erosion and shallow landslides. We suggest that mixtures of different plant functional types would improve soil conservation on slopes, by reducing both surface water erosion and shallow substrate mass movement. Planting trees for cropping or logging, and removing understory vegetation is most likely detrimental to soil conservation.

1. Introduction

Soil degradation on steep slopes throughout the world has accelerated hugely over the last 50 years. In particular, countries such as China have experienced a rapid increase in population density, as well as development and industry. Soil degradation has largely been attributed to poor farming practices, deforestation, road and dam construction (Liang et al., 2009; Stokes et al., 2010; Yu et al., 2006; Zhang et al., 2004). Rehabilitation programs for the reduction of soil erosion can encourage the conversion of cropland to forest and orchards (Cao et al., 2009; Trac et al., 2007). However, one of the assumptions of such conversion programs is that by simply planting trees, erosion processes will be arrested (Trac et al., 2007; Wang et al., 2007; Weyerhaeuser et al., 2005). Thus, trees have been planted for cropping e.g. *Vernicia fordii* or logging purposes, e.g. *Eucalyptus* sp. and

Abbreviations: γ, dried unit weight; Φ, internal friction; Al_{DCB}, Aluminum oxides obtained by dithionite-citrate-bicarbonate extraction; c, cohesion; Fe_{DCB}, Iron oxides obtained by dithionite-citrate-bicarbonate extraction; HWEC, Hot water extractable carbon; MWD, Mean weight diameter; MWD_{FW}, Mean weight diameter after fast wetting; MWD_{SW}, Mean weight diameter after slow wetting; MWD_{MB}, Mean weight diameter after mechanical breakdown; RLD, total root length density; $RLD_{<0.5}$, Root length density for diameter class equivalent or <0.5 mm; $RLD_{0.6-1.0}$, Root length density for diameter class 0.6–1.0 mm; $RLD_{1.1-2.0}$, Root length density for diameter class 1.1–2.0 mm; $RLD_{>2.1}$, Root length density for diameter class equivalent to or >2.1 mm; $rRL_{<0.5}$, relative length density for diameter class <0.5 mm; $rRL_{0.6-1.0}$, relative root length for diameter class 0.6–1.0 mm; $rRL_{1.1-2.0}$, relative root length for diameter class 1.1–2.0 mm; $rRL_{>2.1}$, relative root length for diameter class equivalent to or >2.1 mm; SLCP, Sloping land conversion program; SOC, Soil organic carbon.

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Cryptomeria japonica, but may not be the best solution for soil conservation on steep terrain. Understory vegetation is often removed mechanically or cannot grow in shade conditions, resulting in increased runoff and interrill erosion (Stokes et al., 2010). Root biomass density is usually lower than in natural forest at an equivalent age, augmenting the risk of shallow landslides, particularly during the monsoon season (Genet et al., 2008; 2010).

During heavy precipitation events, splash impact and slaking causes soil aggregates to break down and produce finer, more transportable particles and micro-aggregates. These particles and micro-aggregates (20 to 250 μm diameter) affect the processes of infiltration, seal and crust development, runoff and interrill erosion (Legout et al., 2005, Martinez-Mena et al., 1999). Soil aggregate stability is therefore an important property that may explain, quantify and predict these processes (Zhang and Horn, 2001). Aggregate stability in the topsoil layer (0–5 cm) has also been closely correlated to soil susceptibility to runoff (Barthès and Roose, 2002) and to soil erodibility (Le Bissonnais et al., 2007), i.e. soil susceptibility to detachment and transport by erosion processes.

However, even though a superior aggregate stability may reduce runoff and erosion risk, infiltration may in turn increase, thus augmenting the risk of shallow landslides on steep slopes during heavy precipitation events (Ghestem et al., in press). The only way to resolve this apparent conflict is to ensure that aggregate stability and cohesion are improved simultaneously. A small number of studies over the past 30 years have suggested a link between shallow landslides and erosion processes, although quantitative data relating the two are limited (Al-Durrah and Bradford 1981; Frei et al., 2003; Ghidey and Alberts 1997; Nearing and West 1988; Watson and Laflen 1986). A major factor governing substrate mass movement is the shear strength of soil (Terzaghi 1942). Shear strength within a soil matrix is the result of resistance to movement at interparticle contacts, due to particle interlocking, physical bonds formed across the contact areas (resulting from surface atoms sharing electrons at interparticle contacts), and chemical bonds, or cementation (Craig, 2004). The two major active components in resistance of soil shear stress are i) the cohesion *c*, which is the summation of the effect of particle interlocking and cementation and ii) the internal angle of friction Φ. Φ is the angle measured between the normal force and resultant force that is attained when failure occurs in response to a shearing stress.

One of the earliest studies which investigated the relationship between erosion and soil shear strength was in 1981, when Al-Durrah and Bradford developed a force-resistance model for waterdrop impact detachment based on soil shear strength measured with a fall-cone. Later, Watson and Laflen (1986) related interrill erosion losses to shear strength measured with a torvane on three soils, each with varying slope angle. Nearing and West (1988), used aggregate mean weight diameter (MWD) after disaggregating in water as an indicator of the aggregate stability and shear strength (using a fall-cone and torvane) on three soils contrasting in their texture (clay, silt loam and fine sand). These authors did not find a direct relationship between both parameters, but concluded that water stress influenced similarly the MWD and the bulk soil strength. More recently, Ghidey and Alberts (1997) studied the effect of plant roots on soil erodibility, shear strength and aggregate stability using a rainfall simulator. Ghidey and Alberts (1997) found that as the amount of dead root mass and live root length increased, aggregate stability and shear strength augmented and interrill erodibility decreased. Frei et al. (2003) also found that soil aggregate stability was correlated with soil shear strength from triaxial tests, although the sample number was limited. If a direct link between aggregate stability and soil shear strength could be determined, it would allow a better understanding of the mechanisms involved and thus how of rehabilitation measures influence soils undergoing degradation processes.

The urgent necessity to conserve soil and rehabilitate fragile land on steep slopes worldwide, has led to a number of recent studies investigating the effect of vegetation on aggregate stability and shallow landslides. With regard to the latter, the presence of plant roots physically reinforces the shear zone (see Stokes et al., 2009). However, vegetation can also influence soil structure because of the contribution of organic matter through litter and plant root turnover (Angers and Caron, 1998), root exudates and rhizodeposition (Gyssels et al., 2005; Pohl et al., 2009). The effect of roots on erodibility decreases with increasing root diameter (De Baets et al., 2007). This effect may be due to the higher turnover (rate of root growth and decay, Gale et al., 2000) of fine roots (diameter <2 mm) compared to coarse roots (>2 mm), as well as the association of fine roots with fungal hyphae (Jastrow et al., 1998), and the physically binding dense fine root network. The soil organic carbon (SOC) input in the soil by roots corresponds to temporary binding agents which bind micro-aggregates into macro-aggregates (>250 μm up to several mm diameter) (Gale et al., 2000; Wander and Yang, 2000). Labile fraction of SOC may be assessed by hot water extractable carbon (HWEC). Sparling et al. (1998) found that HWEC after air drying was about 43% of the microbial carbon (i.e. polysaccharides) and strongly related to microaggregation (Boix-Fayos et al., 2001; Ghani et al., 2003; Haynes and Francis, 1993; He et al., 2008; Kouakoua et al., 1997; Von Lutzow et al., 2000). In addition, Fe and Al oxides may interact with organic matter in macro-aggregate stability through their flocculation capacity, the binding effect of clay particles to organic molecules (Zhang and Horn, 2001), and a possible precipitation as gels on clay surfaces (Amezketa, 1999).

The aim of our study was to analyze how soil physical properties were modified under a tree crop, *Vernicia fordii*, where understory vegetation had been removed, compared to a site where the dominant understory vegetation species, *Artemesia codonocephala*, was still present. We also aimed at determining a relationship between soil aggregate stability and shear strength with regard to vegetation type.

2. Materials and methods

2.1. Study site

We studied aggregate stability and soil shear strength in the Yunnan province, Southern China, where erosion and landslides are severe (Yang et al., 2005; Zhang et al., 1995; Zhou et al., 1998).

The study area (26°01′N, 98°50′E) was located near Da Xing Di village, north of Liuku town in the Salween river valley. This part of China is under the influence of the Indian monsoon, and described as a "warm–dry climate", being is a combination of subtropical and alpine climates. Annual mean temperature (from 1961 to 2002) is 15.2 °C, and mean annual precipitation is 1200 mm, the majority of which falls between May and October (Ghestem et al., 2009). Numerous landslides occur during the monsoon season (May–October) and soil erosion is severe, largely due to the cutting of roads through the steep slopes (Stokes et al., 2010).

At our study site, corn (*Zea mays*) was cultivated from 1980, after deforestation, until 1999 when a conversion program was initiated within the framework of the Sloping Land Conversion Program (SLCP). The SLCP, or Grain for Green, aims at planting trees on existing agricultural land, concentrating on zones where slopes are >25° (Cao et al., 2009; Trac et al., 2007). Several species of trees and shrubs were planted at the site, including *Pueraria stricta*, *Ricinus communis*, *Agava americana*, *Jatropha curcas*, and *Vernicia fordii*. We focused on one area where the species *V. fordii* had been established. The oil from its nuts is used for agrofuel production. To avoid competition from the neighbouring biennial pioneer plant, *Artemisia codonocephala,* farmers often remove this latter species through scything.

At our site, two soil horizons exist: an A-horizon in the top 0–15 cm, characterized by a silty clay loam texture (17% sand, 50% silt, 33% clay) and a colour of 7.5 Yr 3/4 (dark yellowish brown); a B-horizon (15–60 cm) dominated by clay (13% sand, 39% silt, 48% clay) and with a colour of 5 Yr 4/6 (yellowish red). Source rock emergence occurred at about 60 cm

depth. Throughout the whole profile, soil was alkaline (pH = 8.42), with a high capacity of exchangeable cations (20 cmol kg^{-1}) and a high carbonate content (15 cmol of $Ca^{2+}kg^{-1}$). Slope angle ranged from 20 to 35° and the site was situated at an altitude of 1000 m.

2.2. Sampling procedure

We selected four plots (5 × 10 m) containing: (i) 4 year old *V. fordii* trees (mean ± standard error diameter at breast height, DBH = 18.66 ± 2.91 cm) in a small plantation with total plant cover of 5%, where *A. codonocephala* was removed through scything on an annual basis; (ii) a combination of *V. fordii* (20% of total plant cover) and *A. codonocephala* (80% of total plant cover), with total plant cover of 60%; (iii) only *A. codonocephala*, with total plant cover of 50% and (iv) a site without vegetation, with plant cover < 5%. In the presence of *V. fordii*, soil samples were collected at 30 cm from the tree base. Six blocks were established within each plot. Each block was circular and was 0.5 m in diameter. Sampling took place at the end of the dry season, from 27 February to 2 March 2010.

For both aggregate stability and direct shear tests, samples were taken from representative typical A- and at B-horizons i.e. at 0–5 cm and at 45–50 cm. Litter, rock fragments and surface crust, when present, were removed prior to sampling. For aggregate stability tests, each sample was 360 cm^3 and obtained using a cylinder corer ($n = 2$ samples from each block, hence $n = 48$ in total). For direct shear tests, samples of soil were removed using a small spade. Each sample was approximately 800 cm^3 and was taken from within three blocks for the plot without vegetation, and from two blocks for plots with *A. codonocephala*, *V. fordii* × *A. codonocephala*, and *V. fordii* ($n = 18$). Samples were kept cool in freezer boxes until they were transported to the laboratory.

2.3. Biotic properties

Once in the laboratory, all roots from soil samples used for aggregate stability tests were removed. To better visualize the roots during image analysis, staining was carried out using an aqueous concentration of 0.1% (w/v) methylene blue, with a contact time of 5 min (Costa et al., 2001). Stained roots were then scanned with a resolution of 600 dpi and analyzed using WinRHIZO (Pro version 3.0, Regent Instruments, Canada) (Zobel, 2008). The total root length and the root length per class of diameter were obtained (<0.5 mm; 0.6 mm–1.0 mm; 1.1 mm–2.0 mm; >2.1 mm). The total root length density (RLD, mm cm^{-3}) was calculated because of its relevance for evaluating the effects of roots on erosion processes (De Baets et al., 2006; Gyssels et al., 2005). The RLD is the total length of the roots divided by the volume of the root-permeated soil sample. The root length density per class of diameter (denoted $RLD_{<0.5}$, $RLD_{0.6-1.0}$, $RLD_{1.1-2.0}$ and $RLD_{>2.1}$, mm cm^{-3}) were also calculated. The relative root length for each class of diameter (denoted $rRL_{<0.5}$, $rRL_{0.6-1.0}$, $rRL_{1.1-2.0}$ and $rRL_{>2.1}$, mm cm^{-3}) were calculated by dividing each root length per class of diameter by the total root length of roots present in the soil sample.

Soil organic carbon (SOC) was obtained by wet digestion (g kg^{-1}) (LY/T 1237-1999 in the Forestry industry standard of the People's Republic of China, 1999). Hot water extractable carbon (HWEC, g/kg) was obtained using a modified method from Haynes and Francis (1993). 6 g of oven dry soil was placed into 100 ml polypropylene centrifuge tubes and 60 ml of distilled water added. The tubes were left for extraction in a hot-water bath at 80 °C for 16 h. At the end of the extraction period, each tube was shaken for 10 s on a vortex shaker to ensure that HWEC released from the SOC was fully suspended in the extraction medium. Samples were then centrifuged for 20 min at 3500 rpm and filtered through Tokyo 5 C paper. Soluble carbon was measured using a Shimadzu TOC-5000 analyser. All analyses were replicated twice.

2.4. Abiotic properties

Soil analyses were carried out on soil fractions finer than 2 mm. Sand (2.00–0.05 mm), silt (0.050–0.002 mm), and clay (<0.002 mm) content were determined using the pipette method (%) (Kalra and Maynard 1991). All analyses were replicated twice. Dithionite-citrate-bicarbonate extractable Fe and Al were measured as described by Mehra and Jackson (1960) (respectively Fe_{DCB} and Al_{DCB}, g kg^{-1}).

2.5. Soil aggregate stability tests

In the laboratory, soil samples were placed in a temperate well-ventilated atmosphere to be air-dried for 1 week. Soil aggregate stability was determined after oven drying at 40 °C, according to the standardized method NF X 31-515 developed by Le Bissonnais (1996). This method combines three disruptive tests, performed on the aggregates of 3–5 mm diameter: (i) fast wetting in water; (ii) slow wetting in water; and (iii) mechanical breakdown. For the fast wetting test, about 5 g of calibrated aggregates was rapidly immersed in 50 ml of deionized water for 10 min. For the slow wetting test, aggregates were capillary rewetted with water on a tension table at a potential of −0.3 kPa for 60 min. For the mechanical breakdown test, similar amounts of aggregates were gently immersed in ethanol. After 30 min, ethanol was eliminated and aggregates were hand agitated in 200 ml of deionized water 20 times in a fast end-over-end movement. The solution was adjusted to 250 ml and was left for 30 min for sedimentation, after which the water was eliminated. After each test, the residual aggregates were collected and transferred onto a 50 µm sieve previously immersed in ethanol, which was gently hand moved in a helical movement, five times with the same amplitude (4 cm) and the same frequency (1 s per cycle) each time. The remaining aggregates on the sieve were collected, and dried at 40 °C for 48 h, and gently dry sieved using a column of six sieves: 2.00, 1.00, 0.50, 0.20, 0.10, and 0.05 mm. Each treatment was replicated three times. Aggregate stability for each sample was expressed as the mean weight diameter (MWD, mm) for each treatment (MWD_{FW}, MWD_{SW}, and MWD_{MB}, for fast wetting, slow wetting, and mechanical breakdown, respectively):

$$MWD = \frac{\sum d \times m}{100}$$

where d is the mean diameter between the two sieves (mm); and m the weight fraction of aggregates remaining on the sieve (%).

2.6. Direct shear tests

Strain-controlled direct shear tests were carried out on reconstituted, drained 60 mm × 60 mm × 20 mm soil samples with roots removed during the reconstitution process. Samples were not saturated prior to testing, and as they were kept sealed at 4 °C after removal from the field, it can be assumed that soil moisture content was similar to that in field conditions. Samples were placed in a shear testing device (VJTech 2760A, U.K.) and normal loads of 200, 300 and 500 N were applied as weights on three separate samples taken from the same block of soil (Schuppener et al., 1999). A lateral displacement was applied at a speed of 0.8 mm min^{-1} until failure occurred and the peak shear force recorded. The cohesion (c) and the angle of internal friction (Φ) were obtained by the Mohr–Coulomb theory (Schuppener et al., 1999).

To obtain soil moisture content, sub-samples were weighed and dried at 60 °C for 4 days and then 105 °C for 24 h, or until constant weight. Soil moisture content was expressed as gram of water per gram of dry soil. Density was measured on each samples tested, using a modified method from Baize (2000) Sample weight was obtained by dividing the volume of water occupied by the sample in a graduated

cylinder. To increase accuracy, the weight of water in the sample was removed from the total sample weight, by calculating the dry unit weight:

$$\gamma = (P/V)/(1-w)$$

where γ is the dried unit weight ($kN{\cdot}m^{-3}$); P the total sample weight (kN); V the sample volume (m^3); and w the soil moisture content (g of water g^{-1} of soil).

2.7. Statistical analysis

Variables were transformed prior to analysis to meet the assumptions required in an analysis of variance (ANOVA), using an arcsine square root transformation for percentage and a log transformation for other values (MWD_{FW}, MWD_{MB}, MWD_{SW}, HWEC, RLD, $RLD_{<0.5}$, $RLD_{0.6-1.0}$, $RLD_{1.1-2.0}$, $RLD_{>2.1}$). The influence of sampling site and horizon on soil properties and aggregate stability was investigated using an analysis of variance (ANOVA). Post-hoc Fisher LSD tests ($p<0.05$) were performed to compare results. The relationship between all variables was investigated using a Pearson's correlation matrix. Linear regressions were carried out to determine the relationships between MWD_{SW} and c and Φ in both soil horizons. Statistical analysis was performed using STATISTICA 7.1 (Statsoft Inc, Tulsa, USA).

3. Results

3.1. Biotic and abiotic properties

The mean RLD, $RLD_{<0.5}$, $RLD_{0.6-1.0}$ and $RLD_{1.1-2.0}$ were significantly higher in the A-horizon compared to the B-horizon ($F_{1,40}=39.84$, $p<0.001$ for RLD, Fig. 1a, $F_{1,40}=36.11$, $p<0.001$ for $RLD_{<0.5}$ Fig. 1b, $F_{1,40}=20.09$, $p<0.001$ for $RLD_{0.6-1.0}$, and $F_{1,40}=4.96$, $p<0.05$ for $RLD_{1.1-2.0}$, Table 1). In the A-horizon, RLD was significantly higher at plots with *A. codonocephala* (8.97 ± 1.31 mm cm^{-3}) and *V. fordii*×*A. codonocephala* (9.32 ± 1.72 mm cm^{-3}) compared to plots with *V. fordii* (4.45 ± 1.17 mm cm^{-3}) and soil without vegetation (2.76 ± 0.78 mm cm^{-3}). In the B horizon, the RLD was significantly lower at plots with *A. codonocephala* only (1.43 ± 0.20 mm cm^{-3}).

Differences between plots were significantly greater with regard to rRL, compared to RLD (Table 1). In the A-horizon, $rRL_{<0.5}$ was significantly higher at plots with *A. codonocephala* (0.75 ± 0.03 mm mm^{-1}) and *V. fordii*×*A. codonocephala* (0.63 ± 0.06 mm mm^{-1}) compared to plots with *V. fordii* (0.33 ± 0.05 mm cm^{-3}) and soil without vegetation (0.29 ± 0.05 mm mm^{-1}). The $rRL_{0.6-1.0}$ was significantly lower at plots with *A. codonocephala* (0.21 ± 0.02 mm mm^{-1}) and *V. fordii*×*A. codonocephala* (0.31 ± 0.04 mm mm^{-1}) compared to plots with *V. fordii* (0.56 ± 0.04 mm mm^{-1}) and on soil without vegetation (0.54 ± 0.04 mm mm^{-1}). A similar pattern was also found with regard to $rRL_{1.1-2.0}$, which was significantly lower at plots with *A. codonocephala* ($0.05\pm$

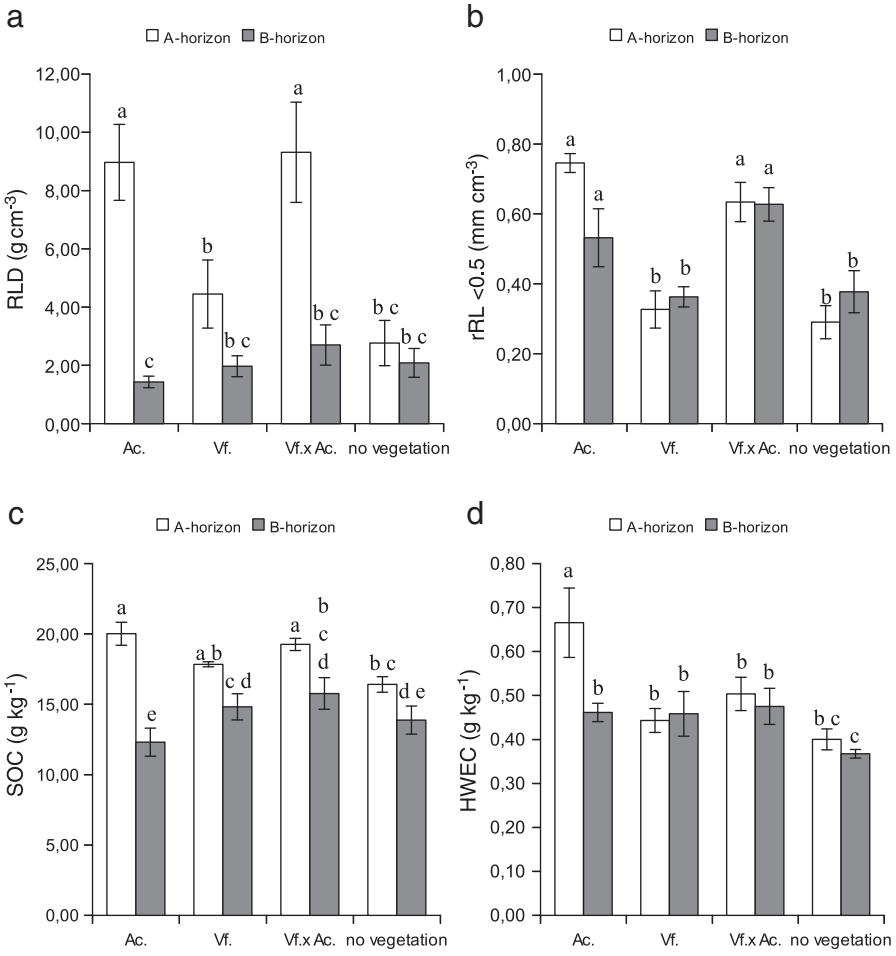

Fig. 1. Main biotic properties measured under the different vegetation types (a): root length density (RLD), (b): relative root length diameter <0.5 mm ($rRL_{<0.5}$), (c): soil organic carbon (SOC) (d): hot water extractable carbon (HWEC). Ac.: *Artemesia codonocephala*, Vf.: *Vernicia fordii*, Vf.xAc.: *V. fordii*×*A. codonocephala*. Values are means±standard error ($n=6$). Where letters above bars differ, data are significantly different ($P<0.05$). F and associated P values are given in Table 1.

Table 1
Vegetation type, soil depth (A and B horizons) and their interaction, influenced aggregate stability, biotic and abiotic variables. F and *P* values were obtained by factorial ANOVA, ($n=48$). MWD_{FW}: mean weight diameter after fast wetting; MWD_{MB}: mean weight diameter after mechanical breakdown; MWD_{SW}: mean weight diameter after slow wetting; RLD: root length density. Values following RLD indicate the roots class of diameter, i.e., <0.5: roots equivalent to or finer than 0.5 mm, 0.6–1: roots with diameter from 0.6 to 1 mm, 1.1–2: roots with diameter from 1.1 to 2 mm, >2.1: roots equivalent to or larger than 2.1 mm. SOC: soil organic carbon; HWEC: Hot Water Extractable Carbon; Fe_{DCB} and Al_{DCB}: dithionite-citrate-bicarbonate extractable Fe and Al.

	Vegetation		Horizon		Vegetation × Horizon	
	$F_{3,40}$	*P*	$F_{1,40}$	*P*	$F_{3,40}$	*P*
Biotic properties						
RLD (mm cm^{-3})	5.96	**	39.84	***	2.72	0.05
$RLD_{<0.5}$ (mm cm^{-3})	11.99	***	36.12	***	2.48	0.11
$RLD_{0.6-1.0}$ (mm cm^{-3})	1.13	0.35	20.09	***	1.04	0.38
$RLD_{1.1-2.0}$ (mm cm^{-3})	0.29	0.84	4.96	*	0.96	0.42
$RLD_{>2.1}$ (mm cm^{-3})	0.71	0.55	0.19	0.67	0.77	0.52
$rRL_{<0.5}$ (mm mm^{-1})	20.10	***	0.42	0.52	2.75	0.05
$rRL_{0.6-1.0}$ (mm mm^{-1})	13.74	***	0.33	0.57	1.75	0.17
$rRL_{1.1-2.0}$ (mm mm^{-1})	4.77	*	1.50	0.23	0.94	0.43
$rRL_{>2.1}$ (mm mm^{-1})	1.14	0.35	1.20	0.28	0.79	0.51
SOC (g kg^{-1})	2.84	*	52.91	***	2.26	0.12
HWEC (g kg^{-1})	6.45	**	4.54	*	2.77	0.05
Abiotic properties						
Sand (%)	1.91	0.14	3.98	0.05	0.89	0.45
Silt (%)	11.68	***	15.44	***	4.32	**
Clay (%)	8.98	***	14.44	***	3.46	**
Fe_{DCB} (g kg^{-1})	11.23	***	2.40	0.13	1,05	0.38
Al_{DCB} (g kg^{-1})	9.42	***	3.09	0.09	2.48	0.08
Aggregate stability						
MWD_{FW} (mm)	1.93	0.14	2.29	0.14	0.81	0.50
MWD_{SW} (mm)	3.26	*	2.44	0.13	1.93	0.14
MWD_{MB} (mm)	3.86	*	3.67	0.06	2.09	0.12

* Significant at 0.05 level, ** significant at 0.01 level, and *** significant at 0.001 level.

0.01 mm mm^{-1}) and *V. fordii* × *A. codonocephala* (0.06 ± 0.02 mm mm^{-1}) compared to plots with *V. fordii* (0.10 ± 0.02 mm mm^{-1}) and soil without vegetation (0.16 ± 0.03 mm mm^{-1}). The $rRL_{>2.1}$ was lower than 0.05 mm mm^{-1} for all plots with no significant differences between plots (Table 2).

The SOC varied from 12.31 ± 0.99 g kg^{-1} to 20.00 ± 0.82 g kg^{-1} (Fig. 1c), corresponding respectively to the B- and A-horizons beneath *A. codonocephala*. In soil from all plots, mean SOC was significantly greater in the A-horizon compared to the B-horizon ($F_{1,40}=52.91$, $p<0.001$). Significant differences were found among different types of vegetation in soil from the A-horizon ($F_{3,40}=2.84$, $p<0.05$). Mean SOC was significantly greater beneath *A. codonocephala* (20.00 ± 0.82 g kg^{-1}) and *V. fordii* × *A. codonocephala* (19.34 ± 0.43 g kg^{-1}) compared to *V. fordii* (17.80 ± 0.18 g kg^{-1}) and soil without vegetation (16.42 ± 0.55 g kg^{-1}). In soil from the B-horizon, only the site with *A. codonocephala* had a significantly lower SOC value (12.31 ± 0.99 g kg^{-1}). Mean HWEC represented 1.59–4.55% of the SOC, the significantly lowest value corresponding to that of soil without vegetation. Mean HWEC was significantly higher in the A horizon compared to the B horizon ($F_{1,40}=4.27$, $p<0.05$, Table 1). In the A-horizon only, mean HWEC was significantly greater ($F_{3,40}=6.60$, $p<0.001$) beneath *A. codonocephala* (0.67 ± 0.08 g kg^{-1}), compared to *V. fordii* × *A. codonocephala* (0.50 ± 0.04 g kg^{-1}), *V. fordii* (0.44 ± 0.03 g kg^{-1}) and soil without vegetation (0.40 ± 0.02 g kg^{-1}).

The quantity of Fe_{DCB} oxides ranged from 18.20 ± 0.64 g kg^{-1} to 24.42 ± 0.71 g kg^{-1} in both horizons (Table 2). The quantity of Al_{DCB} oxides ranged from 2.48 ± 0.11 g kg^{-1} to 3.66 ± 0.21 g kg^{-1} in both horizons (Table 2). The low variability of these two properties did not permit us to study relationships with other variables. The range of values of biotic properties was high in the A-horizon but very low in the B-horizon. Thus, the biotic properties reflected characteristics of the different vegetation only in the A-horizon. Therefore, an analysis of relationships between biotic and abiotic properties and aggregate stability was only possible for data from the A-horizon. In the A-horizon, SOC was found to increase significantly and linearly with an increase in mean RLD, and $RLD_{<0.5}$. Mean HWEC also increased linearly and positively with RLD and $RLD_{<0.5}$ but with a low R^2 (Table 3).

3.2. Soil aggregate stability

Soil aggregate stability was generally low. The MWD_{FW} ranged from 0.37 to 0.56 mm, MWD_{SW} from 0.57 to 1.01 mm and MWD_{MB} from 0.45 to 0.67 mm. Only the two tests of slow wetting (MWD_{SW}) and mechanical breakdown (MWD_{MB}), resulted in significant differences between plots ($F_{3,40}=4.69$, $p<0.05$ and $F_{3,40}=4.15$, $p<0.05$, respectively). The highest MWD_{SW} in the A-horizon was obtained for *V. fordii* × *A. codonocephala*, followed by *A. codonocephala*, *V. fordii*, and soil without vegetation (Fig. 2a). With regard to MWD_{MB} in the A-horizon, the plots with *A. codonocephala* possessed the highest values, followed by *V. fordii* × *A. codonocephala*, *V. fordii*, and the soil without vegetation (Fig. 2b). Between the three tests, MWD_{SW} was the test which best discriminated between plots. Thus, MWD_{SW} was used as the representative parameter, for the ensuing analysis of results.

3.3. Influence of biotic and abiotic properties on soil aggregate stability

As RLD is an absolute value, compared to rRL, it was more appropriate for investigating the influence of root length on MWD_{SW}. In the A-horizon, MWD_{SW} was found to increase significantly and linearly with an increase in mean RLD, $RLD_{<0.5}$, SOC, and HWEC (Fig. 3a, b, c, and d, respectively for MWD_{SW}). No relationships were found between any MWD value for the three treatments and abiotic properties in the A-horizon (Table 3).

3.4. Shear strength characteristics and relationship with aggregate stability

Mean *c* was 15.84 ± 2.33 kPa in the A-horizon and 16.67 ± 0.55 kPa in the B-horizon. Mean Φ was 14.64 ± 3.86° in the A-horizon and 7 ± 0.55° in the B-horizon. No significant differences in *c* or Φ were found between horizons. With regard to results from both horizons combined, no significant relationships were found between γ, *c* and Φ, and no significant

Table 2
Mean value of all measured variables for the different vegetation types at different horizons and results of the post-hoc Fisher LSD tests ($P<0.05$). Mean value ± standard error. Values with the same letters represent homogeneous groups under the significant level of $p=0.5$.

Parameters	Species and horizon of sampling							
	Artemesia codonocephala ($n=6$)		*Vernicia fordii* ($n=6$)		*V. fordii*×*A. codonocephala* ($n=6$)		No vegetation ($n=6$)	
	0–5 cm	45 cm	0–5 cm	45 cm	0–5 cm	45 cm	0–5 cm	45 cm
Aggregate stability								
MWD_{FW} (mm)	0.52 ± 0.09 a	0.51 ± 0.03 a	0.37 ± 0.02 b	0.51 ± 0.07 a	0.53 ± 0.05 a	0.56 ± 0.04 a	0.43 ± 0.03 a b	0.48 ± 0.01 a
MWD_{MB} (mm)	0.67 ± 0.08 a	0.49 ± 0.03 d c	0.53 ± 0.02 a b c d	0.58 ± 0.08 a b c	0.65 ± 0.05 a b	0.62 ± 0.04 a b	0.52 ± 0.02 b c d	0.45 ± 0.03 d
MWD_{SW} (mm)	0.94 ± 0.21a b	0.59 ± 0.03 c	0.59 ± 0.07 c	0.66 ± 0.11 b c	1.01 ± 0.12 a	0.75 ± 0.06 b c	0.57 ± 0.03 c	0.57 ± 0.03 c
Biotic properties								
RLD (mm cm^{-3})	8.97 ± 1.31 a	1.43 ± 0.20 d	4.45 ± 1.17 c	1.97 ± 0.36 c d	9.32 ± 1.72 a	2.70 ± 0.69 c d	2.76 ± 0.78 c d	2.08 ± 0.49 c d
$RLD_{<0.5}$ (mm cm^{-3})	6.73 ± 1.13 a	0.76 ± 0.16 b	1.65 ± 0.60 b	0.72 ± 0.15 b	6.13 ± 1.30 a	1.67 ± 0.41 b	0.83 ± 0.30 b	0.68 ± 0.12 b
$RLD_{0.6-1.0}$ (mm cm^{-3})	1.80 ± 0.24 a b c	0.46 ± 0.13 e	2.37 ± 0.59 a b	0.84 ± 0.12 b c d e	2.69 ± 0.63 a	0.91 ± 0.36 d e	1.52 ± 0.46 a b c d	1.08 ± 0.33 c d e
$RLD_{1.1-2.0}$ (mm cm^{-3})	0.41 ± 0.09 a	0.18 ± 0.07 a b	0.40 ± 0.12 a	0.36 ± 0.16 a	0.48 ± 0.14 a	0.10 ± 0.04 b	0.38 ± 0.11 a	0.32 ± 0.13 a b
$RLD_{>2.1}$ (mm cm^{-3})	0.007 ± 0.004	0.032 ± 0.032	0.033 ± 0.021	0.052 ± 0.025	0.007 ± 0.004	0.023 ± 0.023	0.033 ± 0.033	0
$rRL_{<0.5}$ (mm mm^{-1})	0.75 ± 0.03 a	0.53 ± 0.08 b	0.33 ± 0.05 c	0.36 ± 0.03 c	0.63 ± 0.05 a b	0.63 ± .05 a b	0.29 ± 0.05 c	0.38 ± 0.06 c
$rRL_{0.6-1.0}$ (mm mm^{-1})	0.21 ± 0.02 c	0.30 ± 0.07 c	0.56 ± 0.04 a	0.45 ± 0.04 a b	0.31 ± 0.04 c	0.31 ± 0.04 b c	0.54 ± 0.04 a	0.45 ± 0.07 a b
$rRL_{1.1-2.0}$ (mm mm^{-1})	0.05 ± 0.01 b	0.12 ± 0.05 a b	0.10 ± 0.02 a b	0.16 ± 0.04 a	0.06 ± 0.02 b	0.06 ± 0.02 b	0.16 ± 0.03 a	0.16 ± 0.05 a
$rRL_{>2.1}$ (mm mm^{-1})	0	0.043 ± 0.043	0.012 ± 0.010	0.025 ± 0.012	0	0.005 ± 0.005	0.008 ± 0.008	0
SOC (g kg^{-1})	20.00 ± 0.82 a	12.31 ± 0.99 e	17.80 ± 0.18 a b	14.80 ± 0.93 c d	19.34 ± 0.43 a	15.80 ± 1.12 b c d	16.42 ± 0.55 b c	13.94 ± 1.00 d e
HWEC (g kg^{-1})	0.67 ± 0.08 a	0.46 ± 0.02 b c	0.44 ± 0.03 b c	0.46 ± 0.05 b c	0.50 ± 0.04 b	0.48 ± 0.04 b	0.40 ± 0.02 b c	0.37 ± 0.01 c
Abiotic properties								
Sand (%)	14.27 ± 1.69	10.66 ± 1.69	15.17 ± 3.64	12.65 ± 2.88	19.06 ± 2.14	18.61 ± 2.90	19.38 ± 3.47	10.18 ± 2.41
Silt (%)	44.04 ± 4.46 a	16.70 ± 1.68 c	48.28 ± 4.67 ab	48.17 ± 4.54 ab	55.97 ± 0.78 a	47.86 ± 3.71 a b	50.37 ± 0.99 a b	42.20 ± 6.59 b
Clay (%)	41.70 ± 6.73 b c	72.64 ± 1.73 a	36.54 ± 5.63 b c d	39.19 ± 6.55 b c	24.97 ± 1.76 d	33.54 ± 6.24 b c d	30.25 ± 2.83 c d	47.62 ± 8.52 b
Fe_{DCB} (g kg^{-1})	23.30 ± 0.91 a b	23.93 ± 1.33 a	24.42 ± 0.71 a	22.31 ± 1.55 a b c	20.30 ± 0.30 c d	18.20 ± 0.64 d	20.72 ± 0.50 b c d	20.33 ± 0.47 c d
Al_{DCB} (g kg^{-1})	2.97 ± 0.09 b c	3.66 ± 0.21 a	3.02 ± 0.11 b	2.94 ± 0.16 b c d	2.52 ± 0.08 c d	2.48 ± 0.11 d	2.64 ± 0.14 b c d	2.87 ± 0.27 b c d

relationships were found between biotic or abiotic properties and c or Φ. However, a significant and positive relationship was found between *c* and MWD_{SW} (Fig. 4), using results from both horizons combined together and with a soil moisture content of 24.03 ± 0.80%. This positive relationship was also found to be significant for samples from the A-horizon ($c=25.73\times MWD_{SW}-0.12$, $R^2=0.61$, $p<0.05$) and in the B-horizon ($c=10.97\times MWD_{SW}+9.58$, $R^2=0.48$, $p<0.05$).

4. Discussion

4.1. Variation in aggregate stability

Soil aggregate stability in the A-horizon differed significantly depending on the type of vegetation present. Variations in aggregate stability were negligible in the B-horizon, as also found by Eviner and Chapin (2002). The MWD_{FW} failed to discriminate between the different plots, because aggregate stability was generally too low to resist the high breakdown energy from this test. Inversely, the MWD_{SW} was the best variable to discriminate between plots because it had the lowest breakdown energy. Mean MWD_{SW} was significantly greater in plots of *A. codonocephala* and *V. fordii*×*A. codonocephala* compared to plots without *A. codonocephala*. Mean MWD_{SW} in the A-horizon was greater than 0.8 mm in the two plots with *A. codonocephala* and smaller than 0.8 mm for the two plots without. Therefore, less interrill erosion should occur on plots with *A. codonocephala* during rain events (Le Bissonnais, 1996).

4.2. Influence of vegetation on aggregate stability

The variable best explaining soil aggregate stability in the A-horizon was RLD of the finest roots i.e. in the diameter class <0.5 mm. Similar results were found by Pohl et al. (2009), although these authors could

Table 3
Correlation coefficients (R^2) for the linear relationships between the parameters of aggregate stability and the biotic and abiotic properties ($n=24$) MWD_{FW}: mean weight diameter after fast wetting; MWD_{MB}: mean weight diameter after mechanical breakdown; MWD_{SW}: mean weight diameter after slow wetting; RLD: root length density. Values following RLD indicate the roots class of diameter, namely, <0.5: roots equivalent to or finer than 0.5 mm, 0.6–1: roots with diameter from 0.6 to 1 mm, 1.1–2: roots with diameter from 1.1 to 2 mm, >2.1: roots equivalent to or larger than 2.1 mm. SOC: soil organic carbon; HWEC: Hot Water Extractable Carbon; Fe_{DCB} and Al_{DCB}: dithionite-citrate-bicarbonate extractable Fe and Al.

	MWD_{FW}	MWD_{MB}	MWD_{SW}	RLD	$RLD_{<0.5}$	$RLD_{0.6-1.0}$	$RLD_{1.1-2.0}$	$RLD_{>2.1}$	SOC	HWEC	Sand	Silt	Clay	Fe_{DCB}	Al_{DCB}
MWD_{FW}															
MWD_{MB}	0.796***														
MWD_{SW}	0.852***	0.807***													
RLD	0.265*	0.450***	0.329**												
$RLD_{<0.5}$	0.395**	0.607***	0.459***	0.890***											
$RLD_{0.6-1}$	Ns	Ns	Ns	0.394**	Ns										
$RLD_{1.1-2}$	Ns	Ns	Ns	0.208*	Ns	0.494***									
$RLD_{>2.1}$	Ns	Ns	Ns	Ns	Ns	Ns	Ns								
SOC	0.294**	0.509***	0.461***	0.527***	0.603***	Ns	Ns	Ns							
HWEC	0.401***	0.388**	0.409***	0.255*	0.326**	Ns	Ns	Ns	0.514***						
sand	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns					
silt	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns				
clay	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	0.538***	0.671***			
Fe_{DCB}	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns		
Al_{DCB}	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	Ns	0.684***	

Ns not significant, * significant at 0.05 level, ** significant at 0.01 level, and *** significant at 0.001 level.

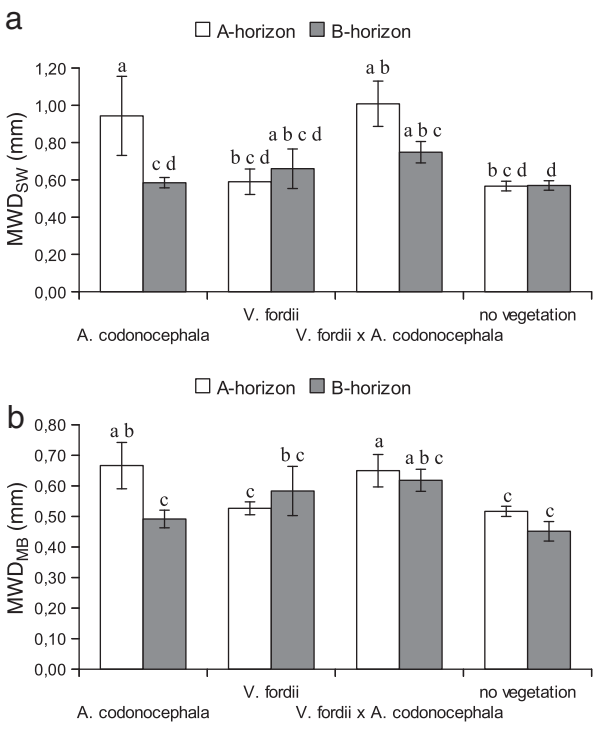

Fig. 2. Mean Weight Diameter (MWD) obtained by from aggregate stability tests (Le Bissonnais, 1996) under the different vegetation types (a) MWD after the treatment by slow wetting (MWD_{SW}), (b) MWD after the treatment by mechanical breakdown (MWD_{MB}). Values are means ± standard error ($n=6$). Where letters above bars differ, data are significantly different ($P<0.05$). F and associated P values are given in Table 1.

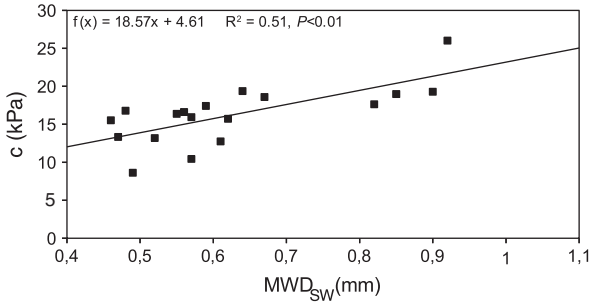

Fig. 4. Relationship between the mean weight diameter after the slow wetting treatment (MWD_{SW}) and the cohesion (c) obtained by direct shear testing in both horizons R^2 is the coefficient of determination at the P probability level.

explain only 10% of the variability in soil aggregate stability when considering roots <0.5 mm, possibly due to the wet sieving method used as an aggregate stability test. Through measurements of RLD, De Baets et al. (2007) also demonstrated the role of roots in the topsoil resistance against interrill erosion. With regard to the different types of vegetation present at our site, total RLD was highest in the plots with *A. codonocephala* and *V. fordii*×*A. codonocephala* and over 50% of total RLD comprised very fine roots (diameter equivalent to or <0.5 mm in these plots). In the remaining plots with *V. fordii* and without vegetation, total RLD was 2–5 times lower and SOC was 5–20% lower in the A-horizon than on plots where *A. codonocephala* was present. Nevertheless, mean RLD was low compared to values from e.g. herbaceous species where mean RLD was approximately 400 mm cm^{-3} (De Baets et al., 2006) and crop species where mean RLD values ranged from 100 to 1000 mm cm^{-3} (Haynes and Beare, 1997). Therefore, even when RLD is small, as in our study, it can still be a useful predictor of aggregate stability.

Plant roots can promote soil aggregation by releasing material which can directly stabilize soil particles, enmesh soil particles by hyphae and roots, or can favour microbial activity in the rhizosphere which in turn will affect soil structure (Bearden and Petersen, 2000; Burri et al., 2009). Very fine roots are more significantly associated

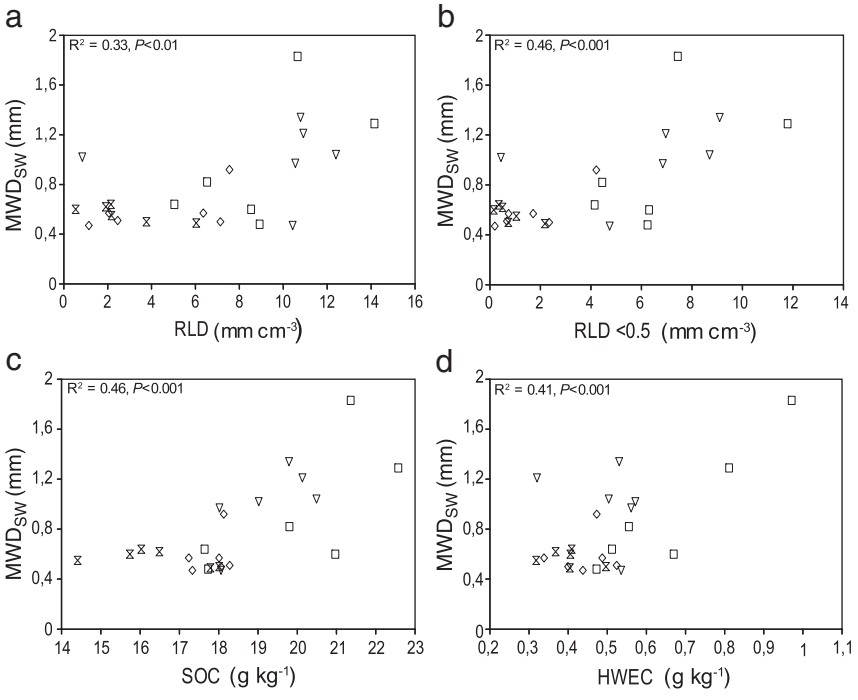

Fig. 3. Relationships between the mean weight diameter after the slow wetting treatment (MWD_{SW}) and the mean biotic properties in the A-horizon (a) relationship between the MWD_{SW} and Root Length Density (RLD), (b) relationship between the MWD_{SW} and the root length density of the class diameter <0.5 mm ($RLD_{<0.5}$), (c) relationship between the MWD_{SW} and the Soil Organic Carbon (SOC), (d) relationship between the MWD_{SW} and the Hot Water Extractable Carbon (HWEC). *A. codonocephala; V. Fordii, V. fordii*×*A. codonocephala;* soil without vegetation. R^2 is the coefficient of determination at the P probability level.

with fungal hyphae (Jastrow et al., 1998) and microbial activity stabilises soil aggregates through the binding action of humic substances and other microbial by-products contributing to soil organic material (Abid and Lal, 2008; Chan et al., 2001; Goh, 2004, Jastrow et al., 1996; Li et al., 2007; Liu et al., 2003; Six et al., 2004; Tisdall and Oades, 1982). In our study, SOC correlated significantly with MWD_{SW} in the A-horizon, although Six et al. (2004) found lower correlations between SOC content and aggregate stability in tropical soils compared to temperate soils. SOC was a better indicator of variability in MWD_{SW} compared to HWEC. This finding contrasts with other studies (He et al., 2008; Kouakoua et al., 1997, Von Lutzow et al.; 2000), where HWEC was better related to aggregate stability than SOC. Kouakoua et al. (1997)) suggested that the quantity of HWEC highly depends on the extraction method i.e. temperature and extraction time. Both SOC and HWEC decreased with increasing soil depth, largely due to the relationship with total RLD and $RLD_{<0.5}$ which were significantly higher in the A-horizon compared to the B-horizon. Organic matter from litter input and mixing may also have contributed to higher SOC and HWEC in the shallow soil horizons (Cerdà, 1998). Nevertheless, mean SOC in the B-horizon was still high (12–16 g kg^{-1}), probably due to past agricultural practices at the field site. Total RLD explained 53% of variability in SOC in the A-horizon and very fine roots (diameter equivalent to or <0.5 mm) explained 60% variability. Roots contribute to SOC through turnover (rate of root growth and decay, Angers and Caron, 1998; Gale et al., 2000) and the exudation of mucilage (Gyssels et al., 2005; Pohl et al., 2009), which is usually greater in very fine roots (Jastrow et al., 1998). As SOC values were high in our study, potential relationships between Fe_{DCB} and Al_{DCB} oxides and aggregate stability were not evident. Duiker et al. (2003) and Igwe et al. (2009), found that Fe_{DCB} and Al_{DCB} oxides content was similar or higher compared to our results and considered these variables responsible for aggregate stability. However, SOC was twice as low as SOC from our study. Similarly, in a study of 18 plots from tropical or subtropical plots around the world, Barthès et al. (2008) found values for SOC comparable to our results, but Fe_{DCB} and Al_{DCB} oxides quantities were much higher than in the soil we examined.

4.3. Relationship between aggregate stability and shear strength

The values for c and Φ lay within the range for clay soils (Magnan, 1991), although values for Φ were lower than those (11–51°) found for non-zonal soil from a debris flow in the Yunnan province (Yang et al., 2005). As shear strength within a soil matrix is the result of resistance to movement at interparticle contacts, physical bonds formed across the contact areas and chemical bonds (Craig, 2004), it is to some extent surface dependent and any action that will hinder or promote the cohesive and frictional forces between adjacent particles will invariably affect shear strength (Ayininuola et al., 2009). We found a significant relationship between soil c and MWD_{SW}, the latter often depending on SOC, root exudates and microbial by-products. Shear strength is thus probably linked to some of the same bonding mechanisms as those involved in aggregation. Therefore, the bonding mechanisms which strengthen aggregates may be similar to those which strengthen interaggregate structure (Bryan, 2000). Thus, vegetation stabilised soil under different hierarchical levels of aggregate organisation (i.e. intra- and inter-aggregate). A similar result was also found by Frei et al. (2003), using triaxial tests on a limited number of samples. These authors demonstrated a significant relationship between c and aggregate stability in moraine soils. Results were attributed to modifications occurring in the soil due to the interactions between roots and fungal hyphae, and presumably subsequent changes in soil chemistry.

Soil cohesion and angle of friction can be influenced temporarily by chemical additions to the soil e.g. calcium sulphate salt, particularly in clay soils which have a large surface area that aids cation and anion exchange among clay minerals (Ayininuola et al., 2009). Nevertheless, data are scanty and significantly more research could be carried out to understand how plant root exudates alter soil chemical bonds and interparticle contacts, thus effecting shear strength. Roots can also physically modify particle contacts in soil through either loosening effects (Yoo et al., 2011) or by compressing soil through penetration, occurring as they push their way through soil (Bengough et al., 2006). However, as tests in our study were on consolidated soil, the physical effect of roots was probably removed. In conclusion, aggregate stability tests cannot replace triaxial or direct shear tests on soil, but may be used as adequate indicators of a soil's stability. Such tests are easy to carry out and do not require the sophisticated equipment necessary for shear testing. However, more tests are necessary on a wide range of soils in different testing conditions.

Our results suggest that soil protection against erosion processes would be improved if understory species e.g. *A. codonocephala* were not removed from beneath plantation trees. Although often believed to result in competition with crop trees, the presence of herbaceous and non-woody species in agroforest systems can actually improve tree growth compared to monospecific tree cultivation (Moreno et al. 2007). Our results indicate that mixtures of different functional plant types would also improve soil conservation on slopes by reducing both surface water erosion and shallow substrate mass movement.

5. Conclusion

We investigated how soil aggregate stability and shear strength differed between sites where the tree crop *Vernicia fordii* had been planted with or without the dominant understory biennial *Artemisia codoncephala*. Aggregate stability in the A-horizon was improved in the presence of *A. codonocephala* and when this species was absent, aggregates were significantly unstable. Soil organic carbon and root length density (for roots equivalent to or <0.5 mm in diameter), were the variables best explaining variations in aggregate stability. A significant positive relationship was also found between aggregate stability and soil cohesion but not internal angle of friction. Results suggest that current techniques of land conversion with removal of understory vegetation around tree crops will increase interrill erosion and soil erodibility and may actually be detrimental for slope stability. As we observed that aggregate stability and shear strength were related, our results showed that there was no contradiction between the improving of aggregate stability, thus reducing surface runoff and erosion, and the decrease in the risk of shallow substrate mass movement by improving cohesion. We explained this result by the beneficial effect of roots on aggregate stability, through rhizosphere exudates and microbial by-products, shear strength is thus probably linked to some of the same bonding mechanisms as those involved in aggregation. Therefore, the bonding mechanisms which strengthen aggregates may be similar to those which strengthen interaggregate structure, and hence cohesion.

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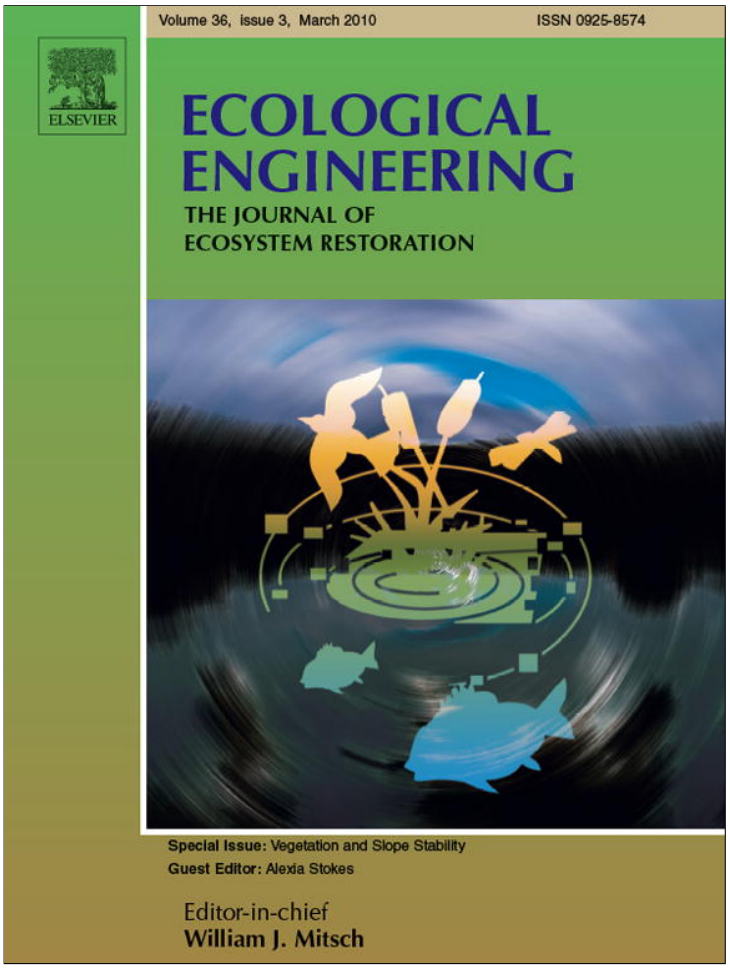

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Preface

Soil bio- and eco-engineering in China: past experience and future priorities

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ABSTRACT

China has the world's longest history of soil bioengineering, with the first mention of giant fascines to control torrential floodwaters dating from over 2000 BC. However, soil degradation on steep slopes has accelerated hugely over the last 50 years, due to poor farming practice, deforestation, road and dam construction. The central government has therefore devised a series of major programs to reduce the exploitation of forest resources (Natural Forest Protection Program – NFPP) and to rehabilitate steep slopes by encouraging the conversion of cropland to forest and orchards (Sloping Land Conversion Program – SLCP). In this review, we define soil bio- and eco-engineering and examine China's past experience in both domains. We focus on case studies whereby vegetation has been used in conjunction with civil engineering to prevent landslides in Hong Kong and the social and practical aspects of planting on steep slopes to conserve soil on a large-scale in mainland China. The successes and failures of tree planting and forest management in the NFPP and SLCP are discussed along with the priorities for future research and practical applications. This review introduces a special edition of the journal *Ecological Engineering*, whereby a selection of papers presented at the Second International Conference 'Ground Bio- and Eco-engineering: The Use of Vegetation to Improve Slope Stability – ICGBE2' held in Beijing, China, 14–18 July 2008, are published. This congress joined together scientists and practitioners with the aim of discussing new theory, methods and applications for using vegetation to fix soil on steep slopes prone to landslides and erosion. In this review, we consider the key points from the conference and place them in the context of managing and restoring degraded slopes in China, one of the world's most pertinent study sites.

1. Introduction

Alterations in land use coupled with the consequences of climate change have led to severe degradation of mountainous and hilly regions around the world. In China, a country where two-thirds of the land is made up of hills and mountains, erosion and landslides are largely the result of deforestation, bad farming practice and over-exploitation of resources in the last 50 years (Liu and Diamond, 2005; Stokes et al., 2008a; Cao et al., 2009). Natural processes such as mountain orogeny, floods, earthquakes also lead to substrate mass movement. The 2008 Wenchuan earthquake in the Sichuan Province caused more than 15,000 geohazards in the form of landslides, rockfalls, and debris flows, directly resulting in over 20,000 fatalities (Yin et al., 2009). China is the most populous country in the world and has to combine sustainable land management with crop production on sloping land, as China currently feeds 20% of the world population and possesses 7% of the world's croplands (FAO, 2007). The Chinese government is well aware of the fragile relationship between crop production and over-exploitation of soil resources and thus is currently searching for new solutions to rehabilitate sloping land. China's scientists, foresters, engineers and farmers are looking for innovative, ecological and economic methods for stabilizing soil against erosion and landslides, particularly on steep slopes. It was therefore highly appropriate to hold the Second International Conference 'Ground Bio- and Eco-engineering: The Use of Vegetation to Improve Slope Stability – ICGBE2' in Beijing, China, 14–18 July 2008. This meeting joined together scientists and practitioners with the aim of discussing new methods for experimental procedures, numerical modelling and with an emphasis on practical applications. A selection of papers presented at the conference are included in this special edition of Ecological Engineering. This preface considers the key points from the conference and places them in the context of managing and restoring degraded slopes in China, one of the world's most pertinent study sites.

2. What is ground, or soil, bio- and eco-engineering?

The terms ground (soil) bio- and eco-engineering have been coined by various authors, but confusion exists as to the exact definition of each. It appears that the term bioengineering was first used as the translation from the German word 'Ingenieurbiologie,' which described the work that encompassed both engineering and biology. The English translation of the first major book covering this topic was called 'Bioengineering for Land Reclamation and Conservation' written by Dr. H.M. Schiechtl in 1980. Over time in North America it became clear that the word 'bioengineering,' which also referred to medical works, was confusing. In 1981, after many discussions with Dr. Schiechtl and other European practitioners, R. Sotir developed the new terminology 'soil bioengineering' for North America. This terminology has also been accepted in other

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parts of the world including Hong Kong and Malaysia. In 1996, a dictionary in English, German, French and Italian was published by vdf Hochschulverlag AG an der ETH Zurich and B. G. Teaubner Stuttgart, entitled 'Dictionary of Soil Bioengineering' 'Woerterbuch Ingenieurbiologie.' In the United States the term 'bioengineering' typically refers to the more simplistic forms of vegetative restoration designed without engineering. Soil bioengineering appears to be synonymous with ground bioengineering, a term employed mainly in the United Kingdom and New Zealand.

Soil bioengineering is defined as a technology that uses sound engineering practices in conjunction with integrated ecological principles to assess, design, construct and maintain living vegetation systems to repair damage caused by erosion and failures in the land and to protect and enhance healthy functioning systems (Sotir, 2002). "Function" is the word that clearly illustrates the need to bridge soil bioengineering and conventional engineering. Thus, while this technology is based both on sound engineering practice and integrated ecological principles, it further views land as systems with integrated functions, rather than merely physically connected structures alone. The value of soil bioengineering then lies in both acceptance and broader understanding of the multifaceted functions operating in the land.

The term 'eco-engineering' was proposed by Barker (1995) as a replacement of the expression 'soil bioengineering,' because of the widespread use of 'bioengineering' in medical science. As a simple replacement of 'bioengineering,' the term eco-engineering was not accepted and thus was later defined by Stokes et al. (2004, 2008b) as the long-term, ecological and economic strategy to manage a site with regard to natural or man-made hazards. An example in a mountainous region could be the correct management of a forest to reduce the impact of substrate mass movement, e.g. landslides, avalanches or rockfall. The differences between soil bioengineering and eco-engineering are largely due to their effectiveness over time and space. In soil bioengineering, from the first moment of installation no erosion should occur as this would be considered part of the original criteria and may be alleviated by the angular arrangement and density of the installed measures. In some cases it is even possible to preorder plant materials for a project and or combine rooted plants with brush that is or is not expected to grow, but functions initially from a mechanical perspective (Gray and Sotir, 1996). However, eco-engineering relies largely on plant growth, therefore during the early years of a restored site, a major window of susceptibility can exist (Sidle et al., 1985; Shi et al., 2004), when plants are too small to contribute much to substrate stability (Genet et al., 2009). In eco-engineering, civil engineering techniques are not used, although local organic material at the site, e.g. logs and stumps may be positioned to prevent soil runoff (see Norris et al., 2008). With regard to soil bioengineering, professional experts are needed to investigate the problem(s) at a given site, to assess, design and install correctly the solution and survey the site in the early years to ensure the mechanical components are functioning and that the vegetative elements are establishing properly. Depending on labor and materials costs, soil bioengineering solutions are often used on a small-scale in high-risk areas. Eco-engineering methods can be more economic on a larger scale and are easily implemented by local foresters and stakeholders after basic training.

3. History of soil bioengineering

The earliest references to examples of bioengineering can be found in Chinese history books. The first ruler and founder of the Xia Dynasty was Yu the Great, born in 2059 BC. Born a civilian, Yu was recruited by King Shun to control torrential river waters and instead of building earthen dikes to contain the flood waters (as his father did before him), he dredged new river channels for nine major rivers, serving as outlets for the torrential waters and as irrigation conduits for farmers. For his efforts of 13 years, King Shun named Yu as his successor, thus founding the Xia Dynasty (Mo, 390 BC; Sima, 109 BC).

Two thousand years later, the governor of Chengdu (Sichuan Province), Li Peng, began work on a massive engineering project to control flood water and used a similar approach to Yu the Great (Murray and Cook, 2002). Inspired by Yu's work, Li Peng devised a system using 'saos' to channel the River Min (called the Du-Jiang Weir, now a UNESCO World Heritage Site). A sao was a gabion or fascine bundle, composed of a mixture of stems and branches of willow and crushed rock tied together with twine or bamboo rope (Fig. 1a). Each sao was several metres long and about half a metre wide and could be placed along the banks of the river or within the river itself, to channel water off from the main river. This channelling system could then be repeated within the smaller channel, thus leading to a system of irrigation for growing crops, an example of which still exists today, near Chengdu (Fig. 1b, Murray and Cook, 2002). Interestingly, the use of the word sao has also been recorded in the Shih-Ching.[1] It was cited that it was not possible to 'sao' (brush away) the plant Puncturevine (*Tribulus terrestris* L.) which was fixed so tightly on walls that it was impossible to pull-out (Anonymous, 600 BC). The use of saos was recorded in Han Shu[2] (by Ban Gu, 32–92 AD) that the great emperor Wu Di, of the Han Dynasty, ordered his soldiers and generals to transport Saos to fix the breached levees of the Yellow River and control the flood water. A section of the Sao-reinforced levee of the Han Dynasty was discovered in 2005 along the Bar River, Shaanxi Province (Huyan, 2006). The technique of making Saos was further refined in the 11th century as recorded in Meng Xi Bi Tan (Dream Pool Essays, hailed as a scientific landmark of ancient China, by Shen Kuo, 1031–1095 AD). At the time, saos were used to close the breaches in the Yellow River dykes that could not be repaired for a long time. The success mainly depended on the placement of the last sao to fill the final gap and fix it in place before the strong current carried it away. A new technique was developed to separate the long sao into three sections connected by ropes and deposit the sections individually to the bottom of the gap before the sao itself began to break away (Needham, 1971). The battle to control torrential river waters continued for centuries in China as the technology to produce saos also improved.

4. Soil bio- and eco-engineering outside mainland China: Taiwan

In addition to China, Taiwan shares the same rich Chinese cultural heritage in everyday living and also has to combat the threat of floods through river management. However, in Taiwan, this threat was never alleviated, therefore, debris flows became increasingly common, and people lost open spaces to ever-rising levees. The concept of bioengineering first emerged in Taiwan around 1998 as the government began experimenting with this concept to preserve natural beauty and animal habitats. Since then, the movement has gained momentum with strong governmental support, and since the 1990 the principals of bioengineering have been viewed as an

[1] The Shih-Ching (or Shi-Jing), is the first book of poetry in ancient China, consisting of folk songs and poetry written by the nobility from 1000 to 600 BC. This book was later edited by Confucius and became one of the Five Confucian Classics used as the basis of all studies.

[2] The book of Han documented the history of China under the Western Han Dynasty from 206 BC to 25 AD.

Fig. 1. (a) Drawing of a bamboo gabion, or sao, published in the Nung Shu (Chinese agricultural treatise) in 1313 AD. The sao consists of rocks bound with strips of bamboo. In (b), a reconstruction of a sao and palisade at Du-Jiang Weir, Chengdu.

alternative engineering solution to achieve the goal of sustainable development while providing flood protection to citizens. In 1999, the Ji-Ji earthquake of magnitude 7.3 struck Taiwan, resulting in the collapse of tens of thousands of buildings and public infrastructures across the nation. To rebuild the disaster area, the government commanded the use of bio- and eco-engineering in the rebuilding process. Close to 3000 projects were completed in the disaster area in the following year, and most of these projects were projects to mitigate debris flow and landslides. Since then, bioengineering techniques have been carried out in various domains (Chen and Lin, 2005). Among the popular methods for strengthening riverbanks and protecting sloping lands is the use of gabion baskets made from galvanized steel wire nettings and filled with crushed stones from nearby areas. It was not until 2007 that the 8th River Management Office of the Water Resource Agency started a distinct local project along the Beinan Creek in eastern Taiwan using bamboo gabions for shore protection works in preference to steel wire gabions. Bamboo gabions blend in with the surrounding environment better and are less visually intrusive. Each gabion weighs about 500 kg and resembles the saos used by the ancient Chinese (Fig. 2).

5. Soil bio- and eco-engineering outside mainland China: Hong Kong

Hong Kong experiences a unique sub-tropical monsoon climate, mountainous topography and heavily weathered soils. Historically, the Hong Kong region has experienced high rates of erosion and slope instability. Due to numerous landslides and associated loss of life, the Geotechnical Control/Engineering Office (GCO/GEO regulatory authority) became very active in the study and implementation of improving slope stability, including studying the level of protection and stabilization that vegetation provided to slopes. In 1984 the GEO began to publish technical guidelines on slope stability mainly from a conventional perspective and their first major publication that included vegetative treatments was published in 2000 (GEO, 2000). While it was largely a landscape document it did incorporate some definitions on soil bioengineering and a number of references, but the main area of interest in this document was man-made slopes. In 2006, a new Special Project Report (SPR, 2006) was produced in which the main focus was on the stabilization and restoration of natural terrain landslide sites and included a broad literature review. Technical guidelines were then developed for the GEO during and after extensive field work which included the setting up of landslide demonstration trials using soil bioengineering measures and an abundance of plant materials which were predominantly native and installed in various configurations and

Fig. 2. Bamboo gabions currently used in Taiwan. (Photograph courtesy of Rui-Lin Chen, WRA Taiwan).

densities. This work led to a Root Investigation Study Report (GEO, 2006), whereby the roots of different plant species used in several soil bioengineering installations were studied at three trial sites. Such data will be most valuable in the development of future soil bioengineering works in Hong Kong.

6. Soil bio- and eco-engineering outside China

At around the same era as Li Peng was working on the River Min, in Europe both Sophocles (496–406 BC) and Pliny (23–79 AD) refer to the need for limiting intensive farming and improving soil conservation on slopes (Stokes et al., 2004). With regard to forests, the first rules recognizing the protective function of forests by limiting forest clearing activities can be found in documents and regulations of the Republic of Venice from as early as the 13th and 14th centuries (Bischetti et al., in press). Since the mid 19th century, the French Office National des Forêts has maintained a department 'Restauration des Terrains en Montagne' which restores degraded forests in mountain areas of France. In the United States and Canada, soil bioengineering was performed on stream and river, lake and levee systems for flood control as well as cut and fill slopes in the 1920s and 1930s. Much of this initial work was forgotten until the 1970s when it began to be revived in western Canada in the restoration of coal mine site operations. This renewed interest led to the translation of Dr. H.M. Schiechtl's major 1973 book originally published in Germany. The translation was published in 1980 by the University of Alberta Press, Edmonton. Alberta Transportation and Utilities Research and Development have been actively interested in soil bioengineering work for many years and carries out feasibility studies in 1984 under the supervision of R. Sotir. This interest has led to the installation of three sites including a steep slope and stream in the Kananaskas area near Canmore and an arctic grayling (*Thymallus arcticus*) spawning stream in Northern Alberta. While these sites were considered costly to install they have proved successful with low long-term maintenance and excellent habitat recovery. Soil bioengineering in North America continues to be strongly influenced by results from these and similar studies, carried out by pioneers in the field (e.g. Gray and Sotir, 1996, now translated into Japanese and Chinese).

In the southern hemisphere, soil bioengineering is widely used in Australia and New Zealand. In both countries, much of the indigenous vegetation has been cleared for human uses since European settlement in the 1800s. The loss of this vegetation has led to a decline in biodiversity and to degradation of waterways through increased sedimentation and nutrient pollution (Phillips et al., 2001; Hubble et al., 2009). In New Zealand, a need for both flood control and revegetation strategies to deal with these problems began to be increasingly recognised from about the 1940s and culminated in the Soil Conservation and Rivers Control Act 1941 (Phillips and Marden, 2006). Current research in New Zealand is largely focussed on the use of indigenous species to reinforce soil (Marden et al., 2005). In Australia, similar problems with waterways were experienced, therefore the early-1990s Australian state governments established Catchment Management Trusts which were made responsible for restoring anthropogenically damaged streams and improving river health (Hubble et al., 2009). These publically-funded bodies mobilised community groups and set about replanting riparian vegetation and re-establishing in-stream woody debris. The reestablishment of riverbank trees is now a major component of Australian public spending on the repair of riverine ecosystems (Brooks and Lake, 2007; Hubble et al., 2009).

Over the last 30 years, advances in both soil bio- and eco-engineering methods have been huge, with the production of several hundred scientific papers, textbooks, project reports and guidelines. Nevertheless, in mainland China, where soil bioengineering existed 2000 years ago, and now a country with some of the highest erosion and soil degradation rates in the world, research into soil bio- and eco-engineering is only just beginning, and is confined largely to contour-strip planting (e.g. Fu et al., 2003; Zhang et al., 2004; see Sun et al., 2008), riverbank restoration (e.g. Li et al., 2006), water and wind erosion (e.g. Gao et al., 2002; Zhang et al., 2005; Zhao et al., 2006; Zheng, 2006; Su et al., 2007; Stokes et al., 2008a,b; Yao et al., 2009), mine reclamation (e.g. Miao et al., 2000) and the rehabilitation of rocky slopes (e.g. Zhu et al., 2009).

7. Soil bioengineering successes in China

Few recent successful soil bioengineering cases have been recorded on steep slopes in mainland China; however, successful projects exist in Hong Kong where heavy monsoon rains cause an average of 350 natural terrain landslides to occur each year. Natural terrain covers approximately 60% of the Hong Kong Special Administrative Region (HKSAR) land area. Due to the size of the area and the frequent occurrence of landslides, the Hong Kong Government is interested in soil bioengineering measures to stabilize and restore these sites. Conventional engineering methods typically used to repair landslides and protect public safety, such as shotcrete and soil nailing, are not appropriate for natural sites due to environmental, aesthetic as well as cost concerns. These conventional methods rely primarily on mechanical support alone and do not consider the biotechnical strengths of plant materials and the importance of natural hillside restoration functions. On such sites, soil bioengineering sets in place a foundation where by which nature can take over, causing the land to become it's own self-supporting, self-sustaining structure. It is believed that the use of soil bioengineering techniques specific to the repair of natural terrain landslides is relatively cheap and the repairs will result in systems that function environmentally and mechanically and blending into the surrounding hillside landscape. To this end, the GEO reviewed natural terrain landslides that occurred in 1999–2001, resulting in the selection of five locations across Hong Kong where there was a high concentration of landslides. These locations included: Cloudy Hill, Tai Po (North and South); Sham Wat Road, Lantau; Lo Lau Uk; Por Lo Shan North and Por Lo Shan South, Tuen Mun. Bare soils were exposed at the landslide scars and loose debris had accumulated down slope (Fig. 3a and b). It was believed that these conditions adversely affected the marginally stable hillsides, and signs of continuing movement had been observed at some of the sites. The GEO saw a need to repair the landslides in order to minimize the chance of more significant deterioration, the possible risk of public safety and substantial costly remediation measures in the future. The work began in 2003 with the GEO selecting Maunsell Geotechnical Services Ltd., Hong Kong in association with Robbin B. Sotir & Associates, Inc., USA, expert in soil bioengineering. This work began with the investigation of some specific 20–25 sites within the Hong Kong Region. It was determined that soil bioengineering could potentially be applied to a wide range of conditions on these recent natural terrain landslide sites, especially given the moderate slope gradients of many site sources – approximately <40°. However, soil bioengineering is not a panacea and was not appropriate for all situations, e.g. deep-seated, rock or extremely steep slopes. Several sites in Cloudy Hill North were selected for the initial soil bioengineering installation measures in 2004 (Fig. 3a and b). The implementions included a combination of living measures i.e. live stakes, live fascines (Fig. 4a) in various configurations, branch-packing, brushlayers (Fig. 4b) and hedgelayers which combined living and structural measures as well as live cribwalls (Fig. 4c) and bender fences. Direct pit plantings of trees and shrubs with

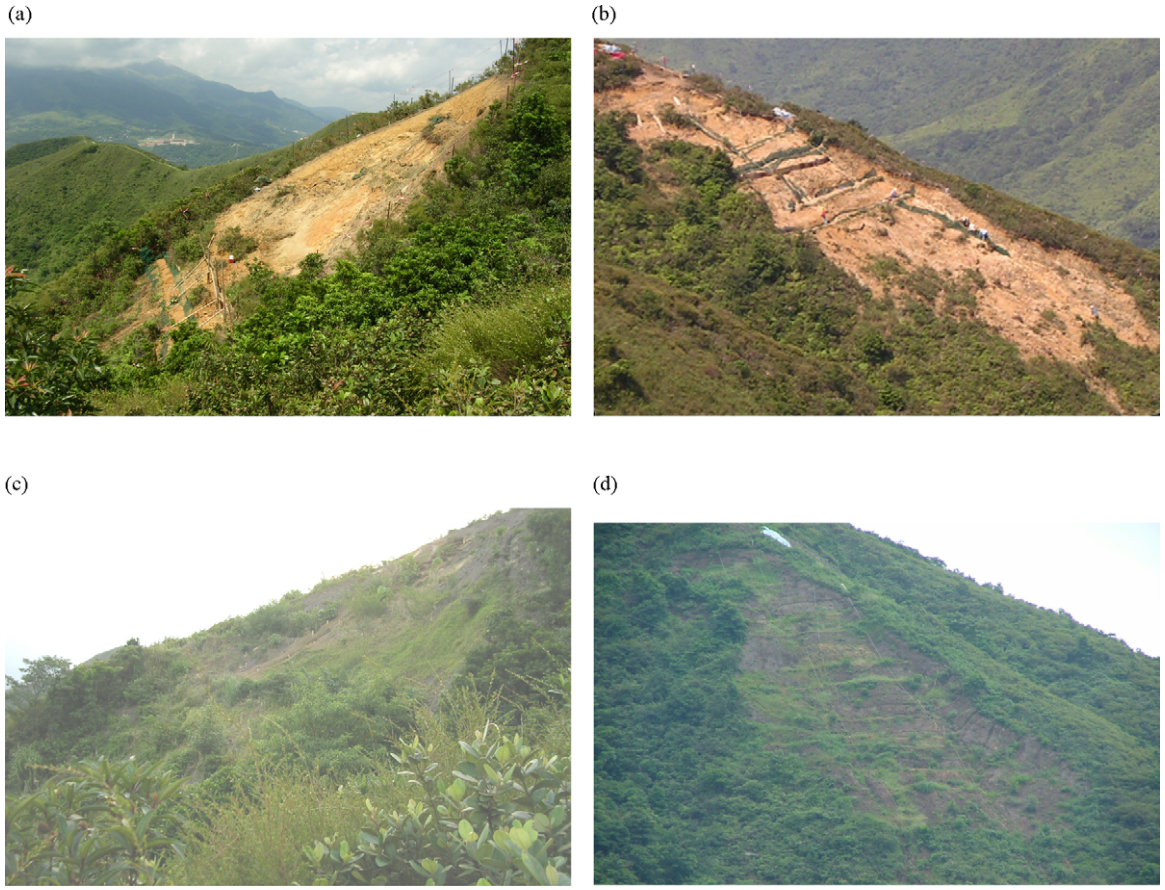

Fig. 3. Soil bioengineering techniques carried out two sites on Cloudy Hill, Hong Kong, China, show that (a and b) vegetation was absent on the landslide scar and bare soil and loose debris accumulated down slope before construction of branchpacking, cribwalls, brushlayers and bender fences and (c and d) 1 year after installation, vegetation was abundant. (Photographs courtesy of Manusell AECOM, Hong Kong.)

mulch cover were also carried out. The cut branch native vegetation species such as *Rhodomyrtus tomentosa*, *Gardenia jasminoides*, *Ficus microcarpa* and *Melastoma candidum* were collected locally and fabricated for each measure on site (Fig. 3). This project also offered an opportunity to learn more about native plant materials rooting capabilities and the performance within each measure. The project performance was satisfactory and each of the three sites have become well vegetated and appear to be establishing as expected and becoming self-sustaining (Fig. 3c and d).

The Hong Kong experience showed that contracting to local companies was not a problem, but more planning was needed to ensure safe access to the landslide sites. Supervision on a daily basis was essential and pre-training was most beneficial. Due to the steep nature of the sites work was performed slowly and weather needed to be closely monitored as the areas were very exposed.

8. The world's largest eco-engineering projects?

China's leaders are well-aware of the rapid degradation of land and the desperate need for a strategy to conserve soil, particularly in steep terrain. Since the 1970s, several national programs have been instigated in mainland China. Ten national forestry eco-engineering projects oriented to soil and water conservation, environmental protection and forest resources expansion have been carried out since 1978. Recently, the Chinese government integrated all former ten forestry programs under the West Development Strategy into six key projects. Among them, the two most important are the Natural Forest Protection program (NFPP) (Weyerhaeuser et al., 2005; Xu et al., 2006; Trac et al., 2007) and the Sloping Land Conversion Programme (SLCP), or Grain for Green project (Feng et al., 2005; Uchida et al., 2005). The NFPP aims (1) to reduce timber harvests from natural (or mixed) forests from 32 million m^3 in 1997 to 12 million m^3 by 2003; (2) to conserve nearly 90 million ha of natural forests; and (3) to afforest and revegetate an additional 31 million ha by 2010 by means of mountain closure, aerial seeding, and artificial planting. By the end of 2002, 3.1 million ha had been afforested, including artificial planting of 1.6 million ha and aerial seeding 1.5 million ha. In addition, 2.3 million ha of mountainous lands had been closed to human activity for forest regeneration (Xu et al., 2006) and from 1998 to 2010, 14 billion US dollars will have been spent on the NFPP. With regard to the SLCP, this program aims at planting trees on existing agricultural land concentrating on zones where slopes are >25°. Farmers have the opportunity to plant medicinal and fruit crops as well as timber species and in 2008, 13.7 million ha land were converted and according to the Central Government, in 2009 alone, a further 5.5 million ha land will be converted (Xinhua Agency, 9 January 2009). Thus, the SLCP has proved to be highly successful and will probably lead to a new 8-year SLCP programme, beginning in 2010. In total, the Central Government aims at converting 15 million ha of agricultural land to forest/orchards. 75% of the new plantations will be with 'ecological forest,' although this includes timber crops and exotic species, e.g. *Eucalyptus* sp. Fruit and medicinal species are restricted on the remaining 25% and intercropping of tree and herbaceous species will not be allowed on target land (He et al., 2009). Farmers in the SLCP programme receive rice quotas

Fig. 4. (a) Live fascines were constructed on-site using *Ficus microcarpa* and *Salix babylomica* species. (b) Brushlayers were installed using *Gardenia jasminoides* and *Melastoma candidum* species and (c) live cribwall was installed using *Gardenia jasminoides* and *Melastoma sanquineineum*, *Phyllanthus emblica*, and *Rhodomyrtus tomentosa* species at Cloudy Hill, Hong Kong, China. (Photographs courtesy of Manusell AECOM, Hong Kong.)

estimated at 1.50–2.55 t yr^{-1} ha^{-1}, depending on the region (hence the title 'Grain for Green' project) as well as funds for buying nursery stock and maintaining plantations (Bennett, 2008). The SLCP Program is thus the most important Payment for Environmental Services (PES) Program ever launched. The core idea of PES is that external beneficiaries of environmental services make direct contractual payments to local landowners and land users in return for adopting land and resource uses that secure ecosystem conservation and restoration (Wunder, 2007). A total of 40 billion US dollars have been budgeted for the SLCP.

The NFPP and SLCP seem successful, but care must be taken when interpreting the above data (Trac et al., 2007). Cases whereby natural forest has been destroyed (through illegal logging or deliberate fire damage) and replanted with exotic timber species are recorded (Feng and Liu, 2006; Zackey, 2007; Stokes et al., 2008a). In 2003, the targeted reduction in timber production on mainland China was reached but since then has not stabilized. The decrease in China's wood production is now also compensated through the importation of logs from Africa, South America or neighboring Asian countries, reaching a total of 95 million m^3 in 2003 (Sun et al., 2004). Illegal importation of wood also occurs (Kahrl et al., 2005). The NFPP promotes afforestation at all costs, thus encouraging the shifting from natural vegetation to man-made forests as a fast restoration of the landscape (Cao et al., 2009). Little thought has been given to how best control soil erosion and slippage. Both the NFPP and the SLCP assume that by simply planting trees, erosion processes will be arrested (Weyerhaeuser et al., 2005; Trac et al., 2007), a dangerous assumption repeated even by some of China's key scientists (e.g. Wang et al., 2007a). Exotic timber species have been planted for logging purposes but, e.g. *Eucalyptus* sp., *Cryptomeria japonica* and *Jatropha curcas* may not be the best solution for soil conservation on steep terrain. Understorey vegetation is often removed mechanically or cannot grow in shade conditions, resulting in increased erosion rates and a lower root biomass distribution than in natural mature forest, with obvious implications for slope stability (Genet et al., 2008). Rotation times may be short, with thinning and clear-felling resulting in windows of susceptibility, where landslide risk is greater (Sidle et al., 1985; Watson et al., 1999). Conversion from crops to forest is often carried out on terraced land where it is still necessary to upkeep terraces to avoid topsoil erosion and prevent water collecting on oversteepened terraces, leading to slope instability (Sidle et al., 2006; Mickovski and van Beek, in press). If the terraces collapse, breaches will focus surface runoff leading to gully formation and increased sediment transport down slope (McConchie and Ma, 2002). Particularly fragile are slopes at the beginning of the rehabilitation process, when trees are young and the root system not developed enough to stabilize deeper soil horizons. Case studies have shown that tree species used for replanting are often not suitable for the local environment and seedling mortality is high (Weyerhaeuser et al., 2005; Trac et al., 2007). Seedling survival varies from one region to another, e.g. is 30% in the north-west of China but only 10% on the Loess Plateau (Wang et al., 2007b). The poor choice of appropriate species indicates the lack of management and knowledge at the county level (Bennett, 2008). In arid and semi-arid ecosystems, the NFPP and the SLCP can be particularly damaging. Cao et al. (2009) found that the destruction of natural vegetation during afforestation led to more erosion and reduced species diversity. Native species should

be preferred, as exotic species can exacerbate soil water shortages. In fragile regions, the simple exclusion of livestock from overgrazed areas and the elimination of cultivation had the biggest effects on the restoration of vegetation cover, whereas tree planting actually had negative effects (Cao et al., 2009). In abandoned cropland on the arid Loess plateau, natural regeneration without human intervention was shown to significantly increase species diversity and cover (Zhang and Dong, 2009). In the sub-tropical Guangdong Province, however, natural regeneration on severely eroded land was slow, whereas planting of, e.g. the exotic *Acacia auriculiformis* resulted in a 90% vegetation cover after 12 years, with the formation of an understorey vegetation community consisting of local species (Wang et al., 2007a).

Lessons learned from the early years of these ambitious 'eco-engineering' programs show that to improve slope stability through replanting, the local ecology needs to be taken into account before a choice of species is made (Li et al., 2003). The limiting factors (precipitation, soil nutrients, air temperature, etc.) need to be ascertained. Information on how to plant young seedlings and prevent mortality in the early years should be given, along with monetary incentives to upkeep the site. The needs of local farmers and villagers should be identified so that species can provide an early income to the local community (Grosjean and Kontoleon, 2009). By providing an income, the maintenance, and hence the conservation, of the slope will be ensured. If crop species are chosen, e.g. the oil producing *Prinsepia utilis* in the Sichuan Province, the possibility of transporting and selling the crop needs to be provided (Trac et al., 2007). Although the central government has ordered that trees be planted in the NFPP and SLCP, it would also have been wise to better consider the role of grasses and herbaceous species for soil conservation. Grasses and herbs can fix soil efficiently on slopes if managed correctly (Loades et al., 2009; Stokes et al., in press). Further socio-economic solutions concerning bureaucracy in particular also need to be considered (Trac et al., 2007; Xu et al., 2007). Not restricted to the Chinese situation only, these basic rules should apply to all bio- end eco-engineering projects around the world.

9. Future priorities

Although environmentalists blame deforestation and agriculture for soil degradation (Stokes et al., 2008a,b), 80% of landslides in China are as a result of human activities, in particular dam-building and road construction. A major new problem to be faced is the building of new roads linking villages to towns. The central government wishes that all administrative towns and villages in mainland China be linked by roads by 2010. The total mileage of rural roads has thus increased from 590,000 km in 1978 to 3.1344 million km at the end of 2007. By the end of 2007, the number of towns and villages reachable by a road accounted for 99% and 88% of the total towns and villages in China, respectively (China Road Construction Report, 2007–2008). This new policy of improving infrastructure in the Chinese interior has resulted in rapid road building. Low-quality roads are often cut into very steep slopes, thus destabilizing the slope and causing major erosion (Fig. 5). For example, a survey along a 28 km road in northern Yunnan, showed that soil loss rates due to road building were over 600 times greater than the highest currently recorded in the USA (Sidle, 2007). Most of the sediment then directly enters the river or is deposited in riparian areas where it is later entrained during floods. In addition, road construction affects many natural habitats and the fauna residing there. An excessive increase in road construction may dissect large patches of land into smaller ones causing habitat fragmentation. This may in turn reduce the living space of animals and bring about detrimental

Fig. 5. Recent accelerated construction of roads linking villages and towns have resulted in all the landslides and erosion visible at this site in the Yunnan province, China. Soil is entrained downslope, resulting in sedimentation of the river Salween (bottom of image), a UNESCO World Heritage Site.

impacts on the species living in the area. Recent research has shown a positive correlation between road development and the reduction in biodiversity (Chen and Chen, 2009). Although the road building will stop in the next couple of years, severe weather events which are predicted as a consequence of climate change will exacerbate the extreme erosion, landslides and resulting sediment pollution. Therefore, mitigation strategies need to be devised so that soil loss and landslides are reduced on steep slopes with newly built roads. Depending on the severity of degradation already incurred, and the consequences of slope failure for infrastructures downslope, soil bioengineering methods should be put into use urgently. However, it is likely that no or little funding will be given to slope stabilization projects in remote areas; therefore, at the very least, guidelines for planting target areas of denuded slopes with local species should be provided to local authorities and villagers. The damage incurred by road building should be treated as a priority by the Chinese government, particularly along river valleys. However, with over 3 million km of rural roads, the devastation could be vast, and requires new solutions for ecological rehabilitation.

As land degradation on China's steep slopes is often on a very large-scale, it is not physically possible to restore or manage correctly such large tracts of land, especially in inaccessible mountain regions. Therefore, mitigation strategies need to focus on target areas of a slope, concentrating on the most fragile zones. Recently proposed as a useful technique for restoring eroded land, the management of degradation hotspots appears to be one of the most economically viable methods for rehabilitating steep slopes on a large-scale. Hotspots are sites with soil degradation rates well above soil loss tolerance levels, e.g. steep slopes with concentrated flow zones after road cutting or gullies with water erosion

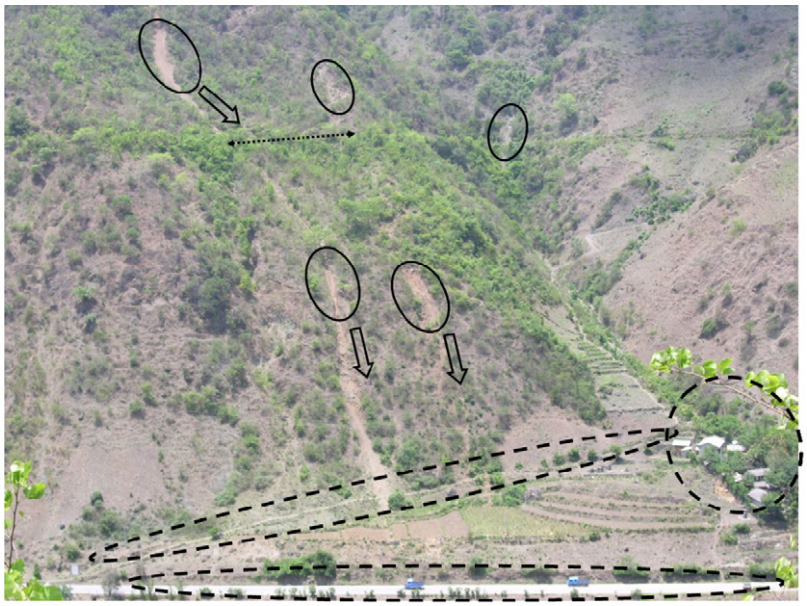

Fig. 6. Soil flow (arrows) occurs from degradation hotspots upslope (circled with solid lines) along Nujiang Valley, Yunnan Province, China. Infrastructure and housing (circled with dashed lines) at the toe of the slope are put at risk if monsoon rains trigger major landslides from these degradation hotspots. The flux of target plant species (dotted line) should be encouraged between hotspots if soil bioengineering techniques are not an option at the site.

(Boardman, 2006; Baigorria and Romero, 2007; Reubens et al., in press). These hotspots often only occupy a small fraction of the whole area, but may be held responsible for a very significant contribution to overall consequences (Fig. 6). Controlling soil degradation at these hotspots is therefore crucial in order to stabilize the soil, conserve soil quality, cut back sediment production and control related off site problems. Once a degradation hotspot is identified and stabilized through managed vegetation, plants will then colonise land nearby, resulting in an economical and low-maintenance solution to a land degradation problem (Boardman, 2006). Research into the processes governing hotspots at a site, how to manage them and the understanding of nutrient, water and vegetation fluxes between a hotspot and a neighboring zone, is limited (see Walker et al., in press). In China, some work has been done on landscape patterns of soil erosion on the Loess Plateau, and suggestions for land management included the planting of shrubland buffers in the zones between the hilltop and the hillslope, and the hillslope to the gully slope (Fu and Chen, 2000). These authors also underlined the importance of not leaving large tracts of land without vegetative cover and suggest that mosaics of different species be planted at given areas along a slope to improve soil fixation (Fu et al., 2003).

How vegetation influences directly soil physical properties on a slope needs to be better understood. For example, species type, mixture and succession processes have been shown to have a direct influence on soil mechanical stability during the restoration process (Pohl et al., in press; Walker et al., in press; Yao et al., 2009). Not only does rooting density influence soil aggregate formation (Pohl et al., in press), but the amount of litter fall and microbial decomposition influences how soil organic compounds bind and coat soil particles, modifying soil wettability and porosity (Yao et al., 2009). Further research in this area could also include how mycorrhizal infection (which varies with plant species and depending on soil conditions) can affect soil mechanical stability during ecological restoration on steep slopes, through either a physical contribution of the mycorrhizal hyphae to aggregate formation (Miller and Jastrow, 1990) or via their influence on root physiological processes (see Lambers et al., 2008). Root tensile strength augments in mycorrhizal-infected roots of some species, depending on soil conditions (Ba, 2008), and root system architecture is often modified during mycorrhizal infection (see Stokes et al., in press). Therefore, mycorrhizas can indirectly but positively influence slope stability. In a growing literature on the subject, mycorrhizas are seen as useful tools in the restoration of degraded soil (e.g. Roy et al., 2007), but again, species and site are important factors to consider before undertaking any rehabilitation project (e.g. Wu et al., 2002; Palenzuela et al., 2002; Estaun et al., 2007). In certain conditions, the introduction of mycorrhizas at a site may even be detrimental (see Walker et al., in press).

One of the current areas where more information is needed is the development of a simple yet elegant slope stability model which takes into account the impact of vegetation and in particular the reinforcing effect of roots (Stokes et al., in press). China's most famous son in this field is Tien H. Wu, who developed a model of additional cohesion taking into account the contribution of roots (Wu, 1976). Used extensively for the last 30 years, various limitations with the model have led to the development and use of a new model called the Fibre Bundle Model (FBM) (Pollen and Simon, 2005; Pollen, 2007; Pollen-Bankhead and Simon, 2009). Tested on several sets of data (Bischetti et al., in press; Loades et al., 2009; Schwarz et al., 2009), the FBM is highly promising but requires further development with regard to the spatial arrangement of roots in soil and the integration of root mechanical properties.

Temporal factors also need considering in models of slope stability. Landslides often occur in periods of heavy rainfall, e.g. during winter in temperate regions and throughout the rainy season in tropical and sub-tropical zones. Fine root growth depends largely on precipitation, soil physical and chemical properties, soil temperature and plant age (see Stokes et al., in press). Therefore, models of slope stability which consider vegetation need root data measured throughout the year as well as throughout the life of a plant. Coupling plant growth models (see Fourcaud et al., 2008), with slope stability models taking into account soil, climate and hydrological factors is ambitious but feasible over the next ten years and would enable the temporal nature of root cohesion to be explored more easily.

10. Conclusion

China has a huge workforce. It is relatively easy to carry out large-scale mitigation actions with regard to soil bio- and eco-engineering. However, once the action has taken place, whether it be the installation of live crib walls or the simple but large-scale planting of trees, a minimum of maintenance is needed on the site, at least during the most fragile period after installation. If the local government does not undertake the maintenance itself, monetary incentives are needed so that villagers carry out the work as well as technical support and a better control of the objectives. Species choice and their appropriateness with regard to site ecology is another weak point in many projects. Economic attractiveness of a species should not be the only criteria considered by local authorities. Planting trees where they simply cannot grow can exacerbate slope stability problems, decrease local plant diversity and result in economic losses, often in already poor areas. In a world experiencing climate change, potential weather scenarios should also be considered during species selection. Species which are currently struggling for survival under, e.g. dry conditions will not be suitable if temperatures increase and water becomes more limited.

Not only will climate affect the success of replanting programs and mitigation plans; if slopes are not managed correctly, substrate mass movement can directly influence the atmosphere and greenhouse gases present. After the Sichuan Wenchuan earthquake in May 2008, it was predicted that the number of landslides caused will result in the cumulative CO_2 release to the atmosphere over the coming decades to be ~105 Tg, i.e. equivalent to ~2% of current annual carbon emissions from global fossil fuel combustion. The nitrogen loss due to biomass decay was twice as much as that released by the 2007 California Fire ($\sim 2.5 \times 10^{-2}$ Tg). A significant proportion of the nitrogen loss (14%) is in the form of nitrous oxide, which can affect the atmospheric ozone layer (Ren et al., 2009). The loss of nutrient rich topsoil during such events reduces the available arable area. For these reasons alone, the international community needs to take an active interest in China's soil conservation problems. Notwithstanding the need to feed a growing population on a diminishing land surface, China is currently the 'World's Factory.' If China wishes to conserve its own forests and sloping land, it still needs raw materials for providing goods for the rest of the world. Legal and illegal logging activities in, e.g. Thailand, Myanmar and the Amazon provide China with wood (Adams and Castano, 2001; Sun et al., 2004; Kahrl et al., 2004, 2005) but the logged trees are not replaced. Therefore, the international community needs to be more actively involved in assisting and facilitating the execution of soil conservation programs in China. For example, contacts and cooperation between governmental and non-governmental bodies on related environmental affairs should be encouraged along with professional and scientific exchanges. More training and expertise should be provided concerning market-based solutions to relevant problems, and the engagement of non-governmental organizations and other institutions could be supported (Xu et al., 2006).

In conclusion, scientists, engineers and practitioners need to work together on an international scale to develop long-term strategies for the ecological management of steep slopes, not only in China but around the world. With this aim, we brought together Chinese and international bio- and eco-engineers to discuss ideas, data and concepts at the Second International Conference 'Ground Bio- and Eco-engineering: The Use of Vegetation to Improve Slope Stability – ICGBE2' held at Beijing, China, 14–18 July 2008. Several papers from this conference are published in this special edition of Ecological Engineering (Bathurst et al., 2009; Bischetti et al., 2009; Genet et al., 2009; Hubble et al., 2009; Loades et al., 2009; Preti et al., in press; Schwarz et al., 2009; Wang et al., in press; Zhang and Dong, 2009). Several more papers are published in a special edition of Plant and Soil (Bischetti et al., in press; Burylo et al., in press; Fan and Su, in press; Mickovski and van Beek, in press; Pohl et al., in press; Reubens et al., in press; Stangl et al., in press; Stokes et al., in press; Tsakaldimi et al., in press; Walker et al., in press). The third conference in this series will be held in Vancouver, Canada, in 2012, and the first author of this paper can be contacted for further details.

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Simulation of direct shear tests on rooted and non-rooted soil using finite element analysis

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ABSTRACT

The finite element (FE) method has been used in recent years to simulate overturning processes in trees and to better comprehend plant anchorage mechanics. We aimed at understanding the fundamental mechanisms of root–soil reinforcement by simulating direct shear of rooted and non-rooted soil. Two- (2D) and three-dimensional (3D) FE simulations of direct shear box tests were carried out using readily available software for routine strength assessment of the root–soil composite. Both rooted and non-rooted blocks of soil were modelled using a simplified model of root distribution and root material properties representative of real roots. Linear elastic behaviour was assumed for roots and the soil was modelled as an ideally plastic medium. FE analysis showed that direct shear tests were dependent on the material properties specified for both the soil and roots. 2D and 3D simulations of direct shear of non-rooted soil produced similar results and any differences between 2D and 3D simulations could be explained with regard to the spatial complexity of roots used in the root distribution model. The application of FE methods was verified through direct shear tests on soil with analogue roots and the results compared to in situ tests on rooted soil in field conditions.

1. Introduction

The ability of vegetation to stabilise and strengthen soil is now well recognised, and this knowledge has been applied to the reinforcement of soil on unstable slopes (Schiechtl, 1980; Coppin and Richards, 1990; Gray and Sotir, 1996; Norris et al., 2008; Stokes et al., 2009; Mao et al., in press). Soil permeated with roots behaves as a composite material in which the roots, considered as inclusions with high tensile strength, are embedded in the soil matrix which itself has a lower tensile strength. Roots thus contribute to an increase in the shear strength of soil through a combination of material and hydrological mechanisms. Robust theoretical models exist for the behaviour of roots in the root–soil matrix (Wu et al., 1988; Pollen and Simon, 2005; Dupuy et al., 2005a; Mickovski et al., 2007; Fourcaud et al., 2008), yet the highly variable nature of both plant and soil properties poses a problem when general models need to be applied to a particular site or vegetation type.

Similar to the soil nails routinely used in geotechnical and environmental engineering, plant roots mechanically increase soil shear strength by transferring shear stress from the soil into tensile forces of the roots themselves, via the interface friction along the root surface. However, the orientation and geometry of the root relative to the shear force (Reubens et al., 2007; Danjon et al., 2008; Bischetti et al., 2010), the skin friction and the material properties of the root (Mickovski et al., 2007) and the area of the shear plane occupied by roots (Wu et al., 1988; Gray and Sotir, 1996), are all factors influencing the reinforcing effect. These factors are difficult to quantify but need to be known in advance if they are to be included in any soil reinforcement model.

Direct shear tests of soil blocks have been conducted in the field (Nilaweera, 1994; Wu and Watson, 1998; Greenwood et al., 2004; Cammeraat et al., 2005; van Beek et al., 2005) and in the laboratory (Shewbridge and Sitar, 1996; Waldron, 1977; Waldron and Dakessian, 1982; Abe and Ziemer, 1991; Gray and Ohashi, 1983; Fan and Su, 2009a,b; Loades et al., 2010), to evaluate the performance of real roots or fibre inclusions designed to simulate roots. Such studies have focused on the direct measurement of the reinforcement offered by roots and derived empirical parameters to be used in slope stability assessment or root reinforcement models. Direct shear tests aimed at the fundamental investigation of

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root–soil interaction mechanisms have also been carried out using 'analogue' roots, i.e. inclusions with material properties close to those of real roots (Abe and Ziemer, 1991; Shewbridge and Sitar, 1996; Mickovski et al., 2007, 2008). These studies showed that soils containing roots with a range of orientations develop wider shear zones and can slowly mobilise reinforcement from roots via their tensile strength even at large shear displacements. These studies also showed that root deformation in sheared soil is influenced by the diameter and concentration of roots. Therefore, slope stability models that consider root strain and the root–soil bond strength in the estimation of root reinforcement will be more accurate. The mechanisms involved in root–soil mechanical interactions have also been modelled using two-dimensional (2D) numerical analyses at the single root or whole plant level. These models aimed at quantifying the effect of geometry and topology on the pullout resistance of roots (Dupuy et al., 2005a) or the overturning resistance of trees (Fourcaud et al., 2008). More sophisticated three dimensional (3D) models have also been developed in finite element (FE) code (Dupuy et al., 2005a, 2007) which showed that root morphological parameters can significantly affect the ability of plants to be well anchored and to reinforce soil.

Analytical (Waldron, 1977; Gray and Ohashi, 1983; Wu et al., 1979, 1988) and numerical (Operstein and Frydman, 2000; Greenwood, 2006; Genet et al., 2008; van Beek et al., 2005; Kokutse et al., 2006) models of soil–root interaction have been derived and used to analyse results of laboratory soil shear tests, bearing capacity tests and slope failures. However, these models need suitable root input data which is not readily available to the engineer in order to be used as predictive tools. Using existing two-dimensional (2D) finite element code and modelling the roots as structural inclusions in the soil matrix may be a preferred approach for an engineer wishing to estimate the effect of roots on soil shear resistance.

The work detailed within this technical paper concerns the simulation of direct shear tests on rooted and non-rooted soil. 2D simulations were performed using existing FE packages for soil analyses (Plaxis® and Diana®), where the roots were modelled as structural elements with known physical and material properties. Models with different numbers of roots were analysed in an attempt to qualify and quantify the effect of root concentration, distribution, and overall stiffness of the root system on the shear strength of rooted soil. The limitations of the 2D approach were then evaluated through a comparison with a more complex 3D model, using Diana®. The results of these simulations are then verified against the results of laboratory and in situ direct shear tests and discussed with regard to the applicability of this type of model for routine rooted soil strength analysis.

2. Materials and methods

2.1. Simulations of direct shear tests using Plaxis®

The FE models described in this study were designed to simulate in situ direct shear tests commonly used to measure the strength of rooted soil (Cammeraat et al., 2005; van Beek et al., 2005; Mickovski et al., 2008; Fan and Su, 2009a,b).

2.1.1. Model simulations

2D models of rooted and non-rooted soil blocks were developed in the geotechnical engineering FE code Plaxis® (www.plaxis.nl). The sides of the soil column and shear box to be simulated were confined and the sides of the shear box displaced at a constant rate, resulting in deformation at the box base. All displacement occurred parallel to the base of the soil column and no out-of-plane strain was allowed. This plane strain idealisation is commonly used in geotechnical models where the dimension in the third axis is relatively large compared to the 2D plane in which most deformation takes place. Consequently, it may be assumed that the soil on either side of this plane provides sufficient constraint to inhibit displacements normal to this plane.

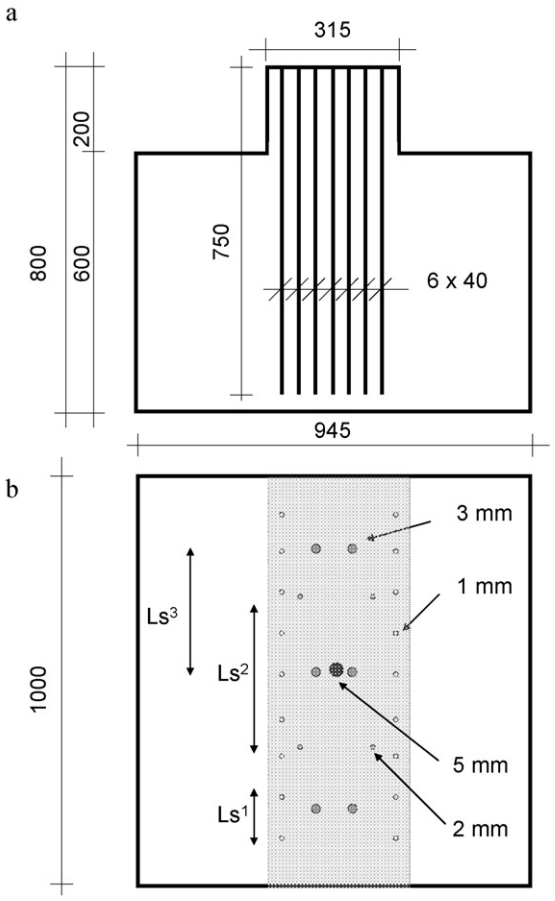

Fig. 1. Cross-section (a) and plan (b) of a typical geometry of a direct shear test model. The multi-rooted model shown includes roots with four different diameters (1, 2, 3 and 5 mm). The hatched area denotes the shear surface. Dimensions in mm. Ls – spacing between roots of same diameter perpendicular to shear. Ls^1 = 100 mm, Ls^2 = 400 mm, Ls^3 = 333.33 mm.

2.1.2. Model geometry

The 2D models (Fig. 1) consisted of an upper layer with dimensions 0.200 m high by 0.315 m wide. The lower soil layer had dimensions 0.600 m high by 0.945 m wide. The out-of-plane thickness in the 2D plane strain analysis was T_{out} = 1 m.

Both single- and multi-rooted models were developed. In the single-root model, the root was placed along the central vertical axis of the model. For the multi-rooted direct shear test, root sizes and distribution reflected those of two perennial herbaceous species: *Brachypodium retusum* and *Ulex parviflorus.* These plants were growing on marly soil near Almudaina, Spain (see van Beek et al., 2005). Root distribution and diameter were measured within soil monoliths 0.315 m wide × 0.315 m breadth × 0.600 m deep (Table 1, van Beek, unpublished data).

2.2. Material properties

2.2.1. Soil

Soil parameters were based on the results of laboratory tests on samples of silty clay from the Almudaina area, Spain (see

Table 1
Root distribution of *Ulex parviflorus* and *Brachypodium retusum* within two soil blocks excavated near Aludhaina, Spain. It was not possible to identify roots of each species, therefore data are for both species together.

Root diameter class (mm)	Number of roots soil block 1	Number of roots soil block 2	Mean number of roots	No. of roots in model (number of groups x number of roots per group)
5.0	0	2	1	1 × 1
3.0	0	10	5	2 × 3
2.0	8	0	4	2 × 2
1.0	10*	30*	20*	2 × 10

* Significant increase in the number of roots compared to roots from other diameter classes using an analysis of variance analysis ($P < 0.05$).

van Beek et al., 2005). The soil properties used in the model include unsaturated and saturated bulk unit weight (respectively, $\gamma_{unsat} = 14.40\,kN/m^3$ and $\gamma_{sat} = 16.40\,kN/m^3$), Young's modulus ($E = 4000\,kN/m^2$), Poisson's ratio ($\nu = 0.325$), effective cohesion ($c' = 6.75\,kN/m^2$), effective internal friction angle ($\phi' = 33.60^\circ$), and dilation angle ($\psi' = 0^\circ$) (van Beek et al., 2005). The soil medium was assumed to have a linearly elastic – ideally plastic behaviour (Mohr–Coulomb). All simulations and analyses were carried out for drained, near-saturated conditions.

The soil was modelled with 15- and 6-node triangular finite elements with 3-point Gauss integration (Fig. 2a). To allow for the possible development of an area with tensile stresses (soil failure in tension rather than in shear) as well as to investigate the effect of allowing tension to develop in the rooted soil, the 'tension cut-off' option was selected for the models run in Plaxis®, using a tensile strength default value of zero.

2.2.2. Interface

The root–soil interface was modelled with 3-noded line elements with the evaluation of axial forces in the corresponding Newton–Cotes stress points (Fig. 2a). An elastic–plastic model was used to describe the behaviour of the interface, based on the Mohr–Coulomb equation. Strength properties of the interface, i.e. cohesion, friction and dilation angles, were linked to the strength properties of the surrounding soil using a reduction factor R_{inter}. In this analysis, this reduction factor was equal to 1.0, i.e. the interface behaved like the surrounding soil.

2.2.3. Roots

Real thin and fine roots usually have a very high tensile strength while their bending stiffness is relatively small (Genet et al., 2005; Mickovski et al., 2007; Norris et al., 2008). For the purpose of this study and to mimic real root material properties, thin and fine roots were simulated with geogrids which are structural elements that can sustain only a tensile load along their length, i.e. they have axial but no bending or compressive strength. Geogrids represent out of plane sheets of fabric in full bonding with the soil and are usually used to model soil reinforcement. The only property in these flexible elastic elements was the elastic axial stiffness $E_{geo} \cdot A_{geo}$ that is given in units of force per unit of out of plane thickness. Axial stiffness was determined by multiplying the Young's modulus E_{geo} by the thickness b of the geogrid. Root models, i.e. geogrid elements, were allowed two translational degrees of freedom in each node (u_x, u_y). The 15-noded and 6-noded soil elements employed the 5-noded and 3-noded geotextile elements, respectively. Axial forces were evaluated at the Newton–Cotes stress points that coincide with the nodes (Fig. 2a).

To take into account the contribution of root clusters to soil reinforcement, it was necessary to scale the geogrid stiffness data, i.e. E_{geo} and b, according to the total stiffness of roots that are considered in the current out of plane. For a group of n roots in a cross-sectional area (CSA) class A_i, the total stiffness of the plane sheet $E_{geo} \cdot T_{out} \cdot b$, where T_{out} is the out of plane thickness of the plane strain model, must be equal to the total stiffness of the roots $n \cdot E_{root} \cdot A_i$, where E_{root} is the Young's modulus of the considered roots. If we take $E_{geo} = E_{root}$, the corresponding geotextile thickness must be $b = A_i \cdot n / T_{out}$.

The properties used for the model roots in the simulations included a generic modulus of elasticity ($E_{root} = 75 \times 10^6\,N/m^2$; Mickovski, unpublished data) and root diameter (d) (Table 1). The plane strain model assumed a plate with a total height of 0.8 m and an out-of-plane thickness T_{out} 1.0 m, as well as a different number n of roots in this direction (Fig. 1) for the multi-rooted model. Root cross-sectional area (CSA) was calculated as $\pi d^2/4$.

2.2.4. Loading and boundary conditions

The loads applied to the model occurred in stages. The first phase applied a gravity load to set up the initial horizontal and vertical stresses in the soil. As stress initialisation by gravity loading produced unwanted soil deformations, these were zeroed at the start of the second phase. The second phase applied the uniformly distributed load, equivalent to a $150\,N/m^2$ normal vertical load placed on the top surface of the upper soil layer. The third and, whenever required, subsequent phases simulated the application of the direct shear load via prescribed displacements along the left- and right-hand-side of the top block. Additional "direct shear" phases have been applied whenever the prescribed shear displacement of 0.083 m was not reached in the current phase (Fig. 2b).

2.3. Direct shear test simulations in Diana®

2.3.1. Two-dimensional study

To compare results with those from the Plaxis® model and to investigate the effect of the tension cut-off, an independent analysis of non-rooted soil was performed using the engineering software Diana® (www.tnodiana.com). The model geometry was the same as that used for the Plaxis® models (Fig. 1). However, the finite elements used in this simulation were 4-node rectangular elements (Fig. 3). In this analysis tensile stress was not allowed to develop in the soil. For comparison with the 2D models analysed in Plaxis® and Diana®, a 'reduced' 2D plane strain equivalent model was derived with the geometry shown by a dashed line in Fig. 3. The loading stages and the boundary conditions were the same as for the model simulations in Plaxis®.

2.3.2. Three-dimensional study

For the 3D simulation of the direct shear test in the software Diana®, a reduced size model derived from the reduced 2D model was analysed to decrease the computational burden associated with 3D analyses. For this study, the soil column had dimensions of 0.315 m × 0.315 m and a total height of 0.80 m. The upper soil layer subjected to shear load was 0.20 m high. After the application of self weight and surcharge loads, the prescribed displacement load was applied along the left and right hand sides of the upper soil layer (Fig. 3) by specifying a multi-point-constraint equation linking the (slave) nodes along the left and right hand sides to a single (master)

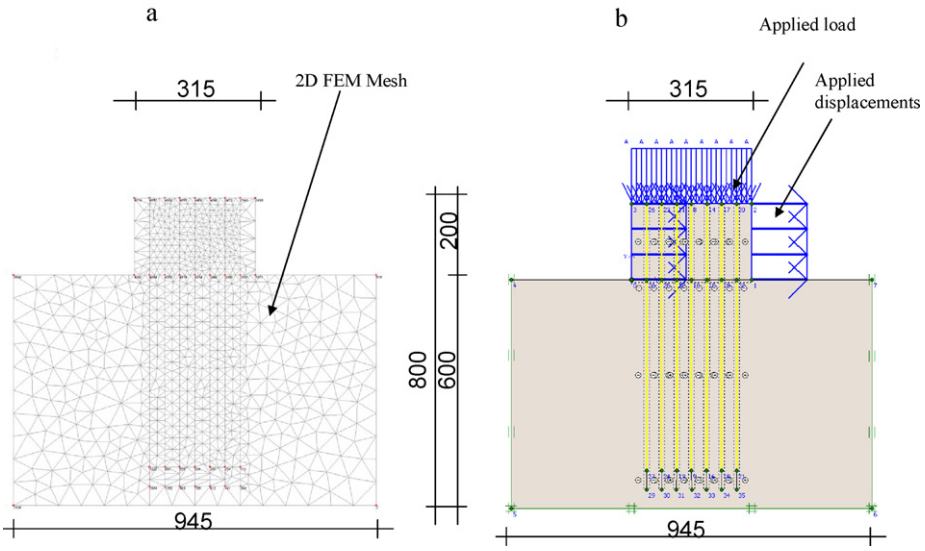

Fig. 2. Finite element mesh (a) and loading (b) for a 2D multi-rooted simulation. Dimensions in mm.

node at one corner of the upper soil layer. The prescribed displacement was applied to the master node and the reaction force output at this node gave the resultant shear load applied to the upper soil layer.

The 'embedded reinforcement' feature in Diana® was used to model the roots in this simulation. Like real thin and fine roots (Genet et al., 2005; Mickovski et al., 2007), these elements only have axial stiffness along their length and locally add stiffness to the elements they are embedded in. Unlike beam and truss elements, they do not require the surrounding elements to match them node for node, which is advantageous from a meshing viewpoint. This type of reinforcement can be useful for complex root systems and in particular for 3D models of rooted soil. However, the embedded reinforcements have some limitations such as specifying 'full bond' or 'no bond' between them and the surrounding material. These elements can only be used in 2D plane strain models if the longitudinal axis of the reinforcement is aligned perpendicular to the plane. Hence, no 2D Diana® plane strain models of the rooted soil were analysed using embedded reinforcements.

For the 3D Diana® study of soil and root blocks, the roots were modelled assuming full bonding with the soil, with root distribution as for the Plaxis® 2D models (Fig. 2.1). No limit on the strength was assigned to the roots in this study where only linear elastic properties were considered, as the roots were considered to have much higher tensile strength than the soil. The interface elements were omitted from the model because of the difficulties in modelling the behaviour of the embedded reinforcements, i.e. roots, across these elements when subjected to transverse load. The loading stages and the boundary conditions were the same as for the model simulations in Plaxis®.

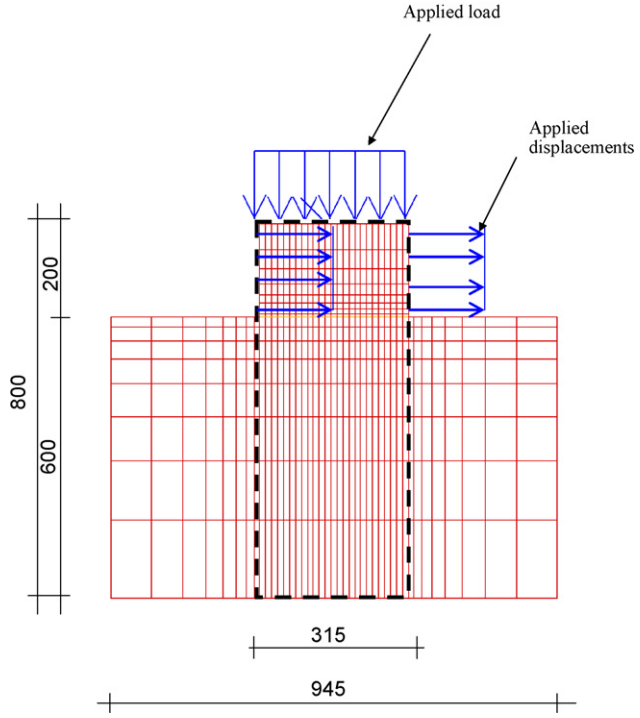

Fig. 3. Model geometry, loading conditions, and FE discretization for a non-reduced (full line) and reduced (dashed line) 2D non-rooted soil direct shear test simulation in Diana®. Dimensions in mm.

2.4. Laboratory direct shear tests on soil permeated with analogue roots

To qualitatively validate the FE models, a range of direct shear tests were performed on soil permeated with analogue roots. The soil, mimicking the strength parameters entered in the numerical models, consisting of 95% silica sand (D_{50} = 0.5 mm) and 5% caolinite clay, thoroughly mixed with water to a soil water content of 12% and left to equilibrate for 24 h. Soil was packed inside a purpose-built direct shear box in 30 mm thick layers to an average bulk density of 2.010 ± 0.027 kN/m^3. Three shear tests under different normal vertical loads (3.65 kPa, 4.24 kPa, and 5.33 kPa) were carried out on fallow soil samples with a view to obtaining the soil strength parameters and comparing them with the laboratory values and field tests on rooted soil.

The custom built in situ direct shear apparatus (Fig. 4) consisted of a 5 mm thick high-density polyethylene box with dimensions 500 mm × 500 mm × 300 mm (plan area 0.25 m^2, volume 0.075 m^3), made of two parts aligned and secured on top of each other. A hand winch was connected to the upper part of the shear box via a digital force gauge (Scaime K25, 10 kN max. capacity, resolution 2.00 mV/V), and strong non-elastic cord (Dynalight®, 6 mm diameter) attached to the box at a specially designed link on the

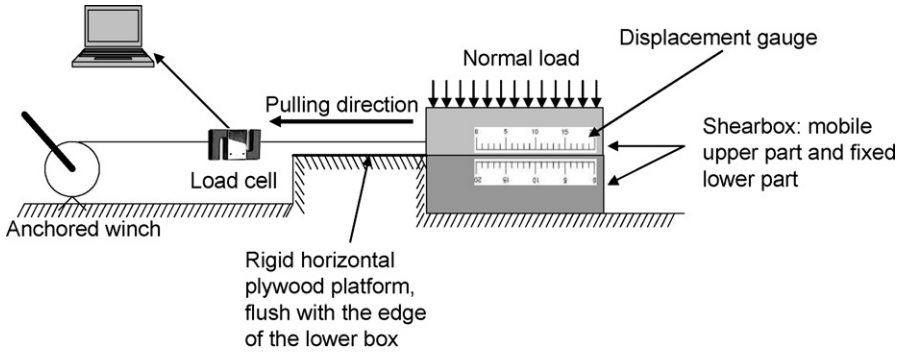

Fig. 4. Schematic of the in situ direct shear test apparatus.

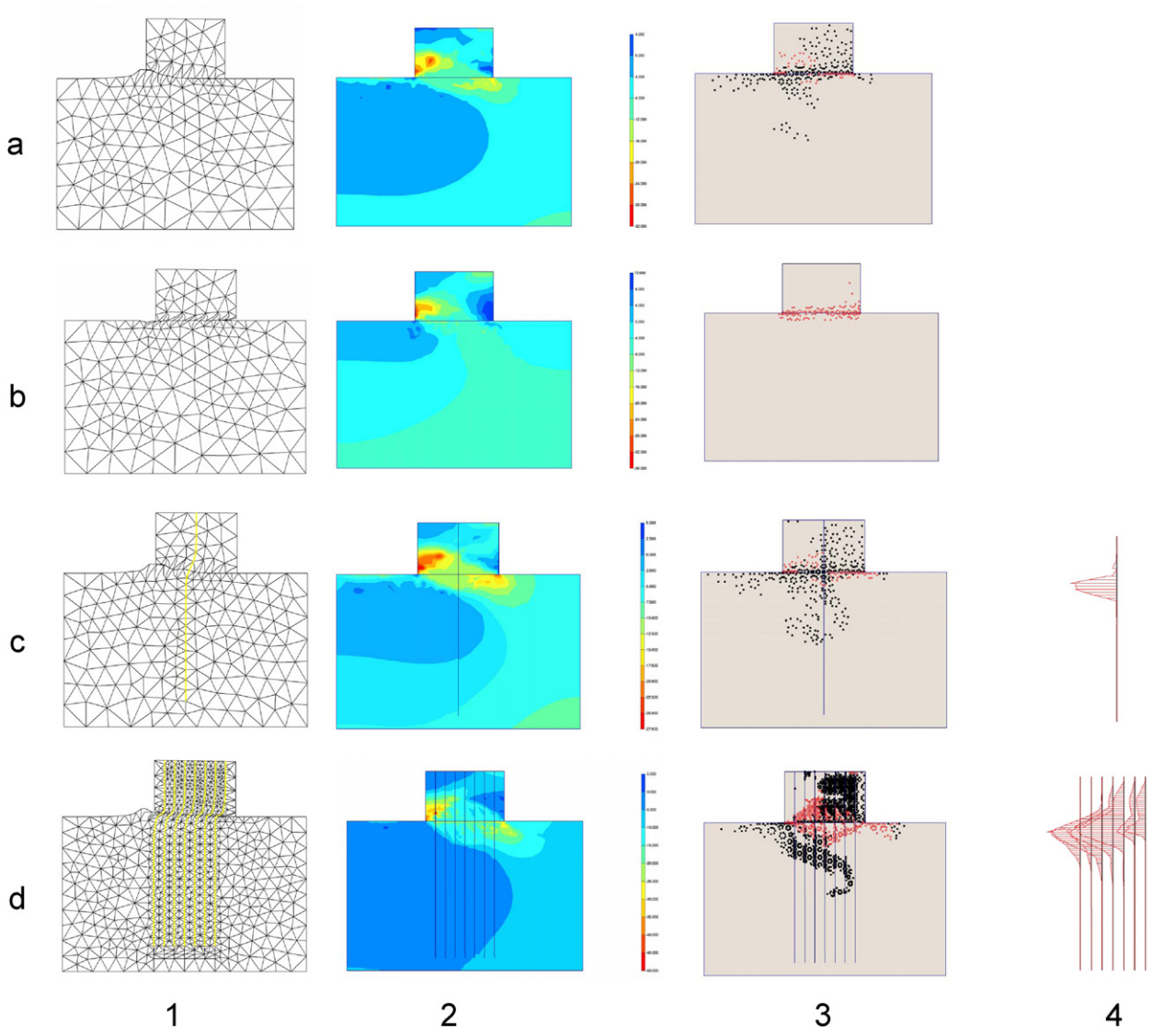

Fig. 5. Deformed mesh (1), mean total stresses distribution, i.e. sum of the three normal stress components divided by three (2), plastic point distribution (3) and axial forces in the roots (4) for (a) non rooted with tension cut-off, (b) non-rooted without tension cut-off, (c) single-rooted with tension cut-off, and (d) multi-rooted with tension cut-off direct shear model. Scale for total stresses (max blue/min red): (1) 4.0 kPa/−32.0 kPa; (2) 12.0 kPa/−36.0 kPa; (3) 5.0 kPa/−27.0 kPa; and (4) 5.0 kPa/−50.0 kPa. In soil mechanics, by convention, positive stress corresponds to compression. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

upper part, while the lower part of the box was kept fixed. The winch was anchored away from the box and in line with the projected movement of the shear box. The winch was turned with a speed that resulted in a 3 mm s^{-1} movement of the upper part of the shear box, thus gradually applying the shearing force while readings from the force gauge were taken every second (using a digital data acquisition system, Ahlhorn AMR ALMEMO 2290-8 V5). The displacement of the shear box was measured using a micrometer gauge fixed on the upper and lower parts of the box.

To simulate the root presence (high tensile strength, low bending stiffness) in the soil, analogue roots made of standard plastic-coated braided copper wire were used. To preserve the relative difference in stiffness between the different root classes in the numerical model while mimicking the equivalent root area ratios for the difference in shearbox size, the 1.00 mm diameter roots from the numerical models were represented with 1.13 mm diameter braided copper wire, 2 mm with 1.78 mm, 3 mm with 2.76 mm, and 5 mm with 4.51 mm of the analogue roots. The analogue roots comprised 300 mm long wire sections, vertically embedded in the shearbox reflecting the multi-root distribution of the numerical models. By suspending the analogue roots in a template above the box, special attention was paid as not to distort or otherwise disturb the analogue root orientation during packing.

Tests on soil replicates permeated with analogue roots were carried out under three different normal vertical stresses (3.82 kPa, 4.30 kPa, and 5.20 kPa) applied to the box via calibrated weights and a load distribution plate.

3. Results

3.1. Direct shear tests model simulations in Plaxis®

The deformed mesh, the stress distribution and the plastic points in the direct shear simulations in Plaxis® are shown in Fig. 5 for (a) a non-rooted case with tension cut-off and (b) a non-rooted case without tension cut-off. Single-rooted (Fig. 5c) and multi-rooted situations (Fig. 5d) are also shown. The direct shear process produced more deformation (heave) where direct shear was applied of the direct shear in the models with a tension cut-off (Fig. 5a, c, and d) than in those without. Consequently, the highest stress concentrations were recorded at the interface between the upper and lower soil blocks on the side where the shear load was applied in all models, and also at the opposite end of the interface in the models with a tension cut-off (Fig. 5a, c, and d).

The inclusion of roots in the model contributed to a general decrease in the magnitude and the distribution of total stresses (Fig. 5a2, b2, c2, and d2). In the rooted models (Fig. 5b–d) the roots were mobilised to resist shear through their tensile strength. This mobilisation was reflected with regard to the maximal axial force in the roots which was 197.00 N/m in the single-rooted model, but in the multi-rooted model, the force was three times higher at 591.97 N/m (Fig. 5c4 and d4).

The distribution of plastic points (Fig. 5a3, b3, c3 and d3) followed the stress distribution and can be used to delineate areas in the soil where failure occurs during the direct shear process. Generally, the inclusion of roots in the model contributed to an increase in the maximum effective normal stress and maximum shear stress in the interface (Fig. 6). Increase in the root CSA contributed to an increase of approximately two fold in both maximum effective stress and maximum shear stress at the interface.

Two non-rooted models were analysed, one with and one without a tension cut-off criterion. For the Mohr–Coulomb soil model as used in this study, the failure envelope was also situated within the tensile normal stress region thus facilitating a tensile capacity. Soil has limited or no tensile strength, therefore, it is more realistic not to specify a tension cut-off criterion. In the non-rooted analyses (Fig. 7), the soil model with no tensile strength allowed (red curve) indicates a stiffer response but a lower ultimate shear load when compared to the soil model with a tension cut-off (blue curve). (For interpretation of the references to color in this figure citation sentence, the reader is referred to the web version of this article.) Allowing tension in the non-rooted model resulted a 10% increase in the maximum normal effective stress and a negligible decrease in peak shear stress.

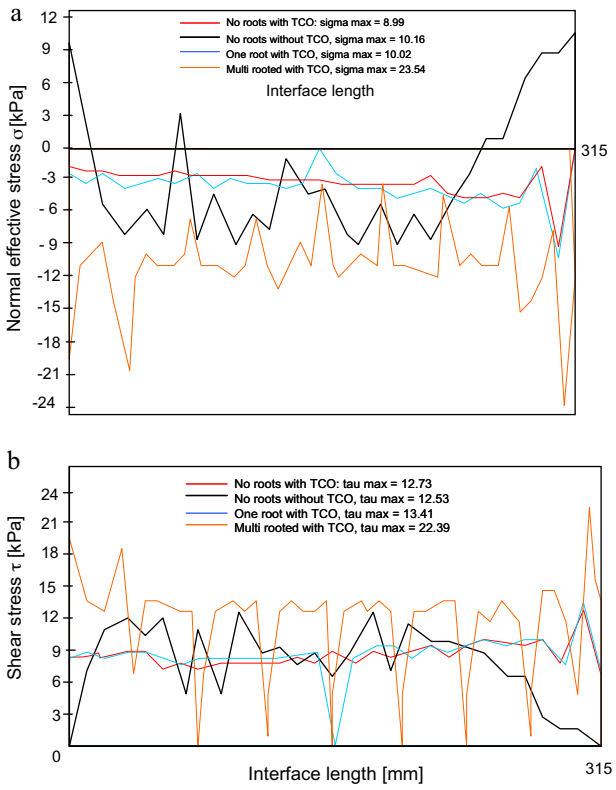

Fig. 6. Distribution of (a) normal effective stress and (b) shear stress along the interface (dimension in mm) for non-rooted (with and without tension cut off), single-rooted, and multi-rooted models in Plaxis®. Solid line in (a) is interface length.

During the direct shear simulations in Plaxis®, the maximum shear load increased rapidly in the first 2 mm displacement in

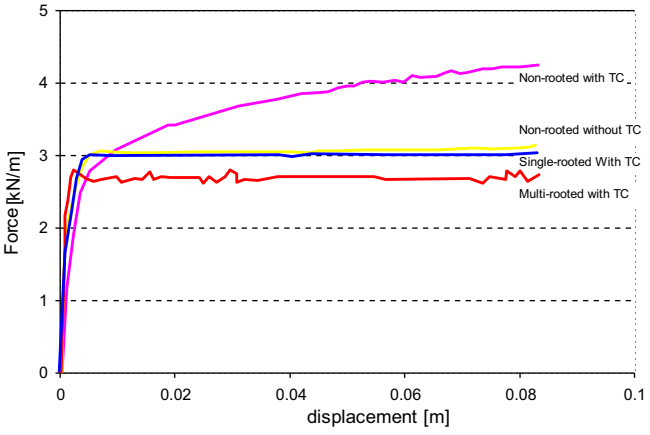

Fig. 7. Global load displacement response for simulated non-rooted, single and multi-rooted soil against in situ tests: non-rooted with tension cut-off, non-rooted without tension cut-off, single-rooted with tension cut-off, and multi-rooted with tension cut-off.

all models (Fig. 7). The non-rooted model without tension cut-off reached a peak (2.8 kN/m) at a displacement of 3 mm before levelling off. The non-rooted and the single-rooted model with soil tensile capacity demonstrated very similar behaviour when reaching the maximum shear strength of approximately 3 kN/m at 6 mm displacement before levelling off, with the single-rooted model showing a marginally higher ultimate shear load. The multi-rooted model, however, showed a distinctly different behaviour with increasing shear load throughout the displacement range.

The Plaxis® analysis of the single-rooted soil (Fig. 7) indicated a marginally higher ultimate shear load than the non-rooted case. The Plaxis® prediction for the non-rooted case at 80 mm displacement was around 2.8 kN/m (3.1 kN/m for the model with tension cut-off and 2.6 kN/m without tension cut-off) which is equivalent to a shear stress of 8.8 kPa. The analysis where the tensile stresses were allowed to develop (without tension cut-off) predicted a value of 8.1 kPa. The model with suspended tension development (with tension cut-off) predicted a much higher value of maximum shear stress of 9.8 kPa.

For the multi-rooted analysis, Plaxis® predicted a shear load of around 4.2 kN/m at 80 mm shear displacement, equivalent to a shear stress of 13.3 kPa.

3.2. Direct shear tests model simulations in Diana®

3.2.1. 2D study

The direct shear test on non-rooted soil without a tensile capacity carried out in Diana®, predicted an ultimate shear load of around 2.35 kN/m [7.5 kPa], 13% lower than the 2.7 kN/m [8.6 kPa] as predicted by the equivalent Plaxis® analysis (Fig. 8). The analysis of the normal and shear stresses developed in the interface demonstrated a peak normal stress of 10.16 kPa and a maximum shear stress of 11.50 kPa, which was similar to the parameters obtained with the equivalent analysis in Plaxis® (peak normal stress of 8.50 kPa and a maximum shear stress of 12.53 kPa).

3.2.2. 3D study

The deformed shape of the non-rooted soil under direct shear load with total displacements superimposed onto the deformed mesh is shown in Fig. 9a. The maximum shear load in this simulation was 1.0 kN at 83 mm displacement which, for a 0.315 m out-of-plane thickness, was equivalent to a shear stress of 10 kPa. The deformed shape of the multi-rooted soil under direct shear load is shown in Fig. 10. For this model, the maximum shear load at 83 mm displacement was 3.06 kN/m [30.6 kPa], which was two times greater than that predicted in the Plaxis® 2D plane strain model using geogrid elements: 4.3 kN/m [14 kPa] for a displacement of 83 mm. It needs to be noted that this simulation where the effect of the surrounding soil in the zone below the shear plane was not taken into account closely corresponded to the boundary conditions of a standard laboratory direct shear test.

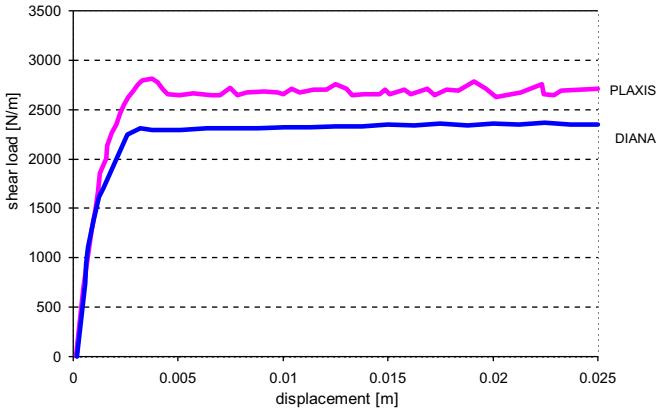

Fig. 8. Comparison of the direct shear test simulations for non-rooted soil without tension cut-off in Diana® and Plaxis®.

A typical axial stress distribution for a 5 mm diameter central root at 0.043 m shear displacement is shown in Fig. 10. As expected, the peak axial stress occurred at the interface between the upper and lower soil blocks at a distance of 0.2 m from the top surface. This result was also observed for the Plaxis® 2D studies (Fig. 7).

The 'reduced' 2D plane strain model of the non-rooted case resulted in a peak shear load of 2.7 kN/m which, for a 0.315 m out-of-plane thickness, equates to a shear stress of 8.7 kPa. The 'reduced' 2D plane strain model was compared with the 2D Diana® model (Fig. 9) to study the effect of the surrounding soil. The consideration of the soil on either side of the lower soil block contributed to

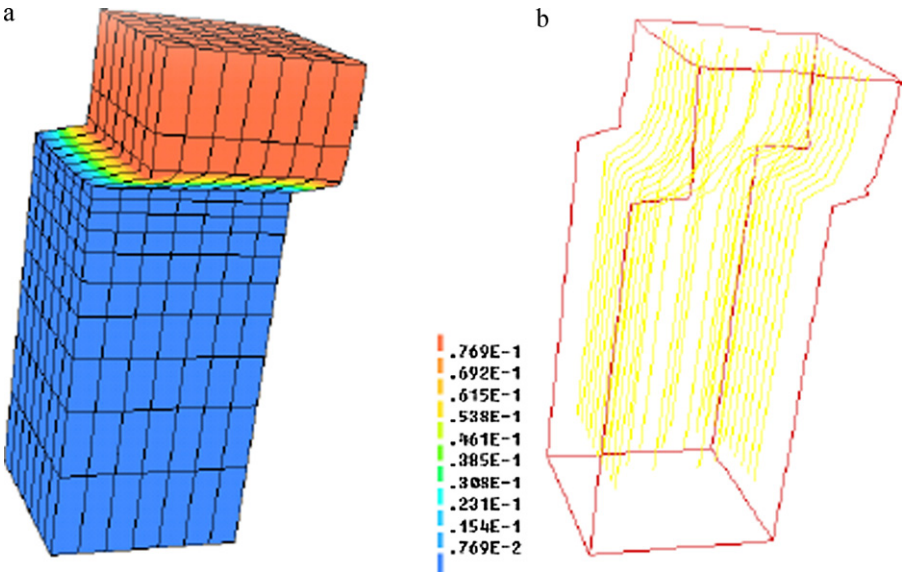

Fig. 9. Deformed shapes of the (a) non rooted and (b) multi-rooted soil under direct shear loads. Total displacements (in m) were superimposed onto the non-rooted deformed shape.

Table 2
Peak shear load predicted from the 2D Diana® model with different levels of mesh refinement.

Number of finite elements in model	Peak shear load (kN/m)
105	3.597
262	3.220
1048	3.020
4024	2.943

a higher predicted peak shear load than that for the reduced geometry with no soil on either side (3.6 kN/m [11.4 kPa] cf. 2.7 kN/m [8.7 kPa]).

The 2D Diana® model was run without the interface elements between the upper and lower soil blocks for an equivalent comparison with the 'reduced' 2D plane strain model. The analysis without interface elements predicted a higher peak shear load than the model with interface elements. For increasing levels of refinement, the solutions for the 2D Diana® model without the use of interface elements (Table 2) tended to converge towards the Diana® solution with the use of interface elements where the peak shear load was around 2.35 kN/m [7.4 kPa].

3.3. Laboratory direct shear tests on soil permeated with analogue roots

The shear load in the fallow soil samples (a typical load *vs* displacement curve is shown in Fig. 11a) increased sharply in the first stage of the test, reaching a peak at approximately 5% (median value) strain before levelling off or decreasing to the value of residual shear resistance. In contrast, the shear load of the samples with analogue roots (Fig. 11a) augmented in the first stage of the test and then continued to increase slightly, reaching a peak at approximately 25% strain (median value), indicating increased ductility of the sample when compared to the fallow soil tests. The peak shear force and the calculated peak shear stress obtained through the laboratory shear tests on samples of fallow soil and soil permeated with analogue roots showed that the inclusion of analogue roots typically resulted in an increase of 33% in peak shear resistance (Table 3).

Fallow soil possessed an angle of internal friction of 28.5° with effectively no cohesion ($c' = 0$ kPa). However in laboratory tests, the angle of internal friction was 33.8° with an effective cohesion of $c' = 3.8$ kPa obtained via standard laboratory quick undrained small shearbox tests (AFNOR NF P94-071-1) on representative samples of the same soil and the parameters used in the numerical models ($\phi' = 33.6°$, $c' = 6.75$ kPa). However, in soil permeated with root

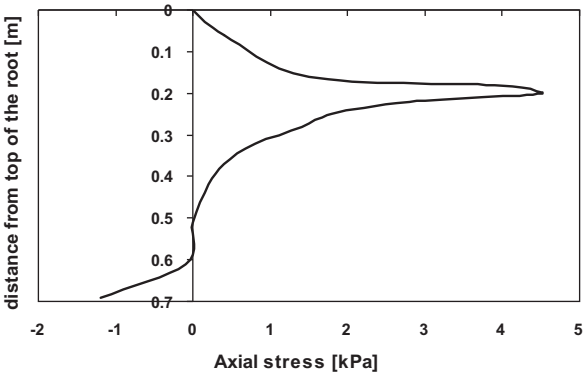

Fig. 10. Typical axial stress distribution for a 5 mm diameter central root at 0.043 m shear displacement.

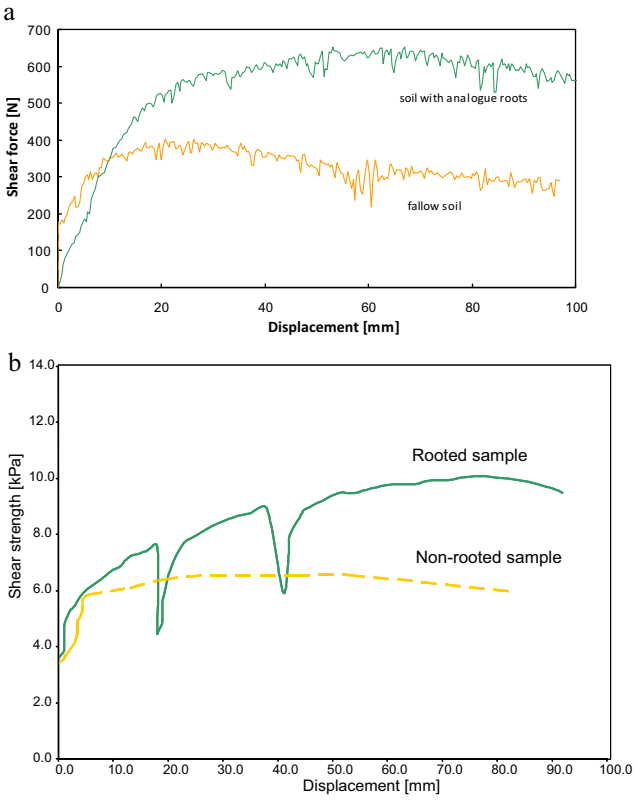

Fig. 11. Typical shear behaviour of fallow soil and rooted soil (a) with analogue root samples during the in situ shear tests and (b) with roots of *Vetiveria zizanioides* (Mickovski and van Beek, 2009).

analogues, the internal friction angle increased slightly to 29.2° and the effective cohesion to $c' = 0.35$ kPa.

4. Discussion

For the purpose of this technical paper, existing FE packages were used to perform 2D simulations of direct shear tests on rooted and non-rooted soil. The roots in the rooted models were modelled as structural inclusions with linear elastic properties embedded in an elastic-ideally plastic soil matrix. Soil permeated with different numbers of roots was simulated along with fallow soil (no root inclusions). Additionally, the effect of allowing tension to develop in the soil matrix was investigated. The limitations of the 2D approach were evaluated through a comparison with a more complex 3D model.

Using numerical modelling, the distribution of shear stresses in the root–soil continuum during shear was visualised together with the stress distribution along the roots and on the shearing inter-

Table 3
Peak shear load obtained in the laboratory shearbox tests and calculated peak shear stress.

Normal vertical stress (kPa)	Peak shear load (kN/m)	Peak shear stress (kPa/m)
Fallow soil		
3.65	0.81	3.24
4.24	1.22	4.88
5.33	1.34	5.36
Soil with analogue roots		
3.82	1.26	5.04
4.30	1.36	5.44
5.20	1.64	6.56

face. This will help engineers and eco-engineering practitioners to understand the complex phenomena occurring during shearing events (e.g. landslips) and evaluate the morphological and strength parameters required from a root system that can withstand shearing at a certain depth. As expected, the presence of roots, modelled as structural geotextile elements (geogrids) or embedded reinforcements, contributed to an increase in the overall strength of the soil. A marginal increase in shear strength was observed in models with only one single row of 0.5 mm diameter roots. However, a more significant increase was observed when multiple rows of roots existed.

The models incorporating a tension cut-off criterion indicated a less stiff response and a higher ultimate shear load capacity than the models in which tensile stresses were allowed to develop. The higher ultimate shear load capacity was due to the full tension in the direction of shear that was allowed to develop at zero normal stress for the model incorporating a tension cut-off. In the case without a tension cut-off, the stress states within the tensile region had a shear strength lower than the tension in the direction of shear, which is the actual value of soil cohesion. The Diana® calculations were performed without tension cut-off in contrast to the Plaxis® 2D calculation. We attempted modelling tension cut-off via a brittle cracking model with a nominal low tensile strength and a full shear retention criterion in Diana® but problems with solution convergence were experienced. However, it is possible that the specification of brittle cracking in which the strength falls to zero once the tensile strength has been reached may have been too severe. In future studies utilizing Diana®, the use of a tension-softening criterion rather than brittle cracking should be investigated.

The analysis of the load-displacement response of the models analysed in Plaxis® showed that the single-rooted model does not significantly increase soil shear resistance compared to the non-rooted model. However, the multi-rooted model, where the area occupied by roots over the shear surface was much higher, had a significantly greater resistance to shear reflecting the increase in root cross-sectional area. The behaviour of the multi-rooted models also closely resembled the behaviour of rooted soil samples sheared in laboratory studies (Mickovski et al., 2008) as well as the samples with analogue roots in the in situ tests, where the shear load increased constantly throughout the whole range of shear displacements.

The effect of precluding the interface elements from the Diana® analysis resulted in a higher predicted global shear load than the Diana® model which incorporated interface elements. The exclusion of interface elements also indicated that the solution was dependent on the level of mesh refinement. The global shear load was seen to decrease as the number of degrees of freedom in the model increased (Table 2). The solution appeared to converge towards the interface element solution.

The difference between the results of the direct shear simulations of multi-rooted soil in 2D and the 'reduced' 2D plane strain models could be explained by the fact that in the 3D Diana® study, from which the 'reduced' 2D plane strain model was derived, the distribution of the multiple roots was explicitly defined over a length of 0.315 m whereas in the Plaxis® 2D plane strain model the roots were assumed to be distributed over a 1 m out-of-plane length (Table 1 and Fig. 1). The overestimation of the peak shear stress in the 3D model compared to the 2D is thought to be due and not limited to the fact that no interface elements have been inserted between the upper and lower soil blocks nor between the roots and the soil. The narrowness of the block may also lead to a very stiff lower body that influences the generation of stresses. As a result of this, no shear load was being transferred across the small length of embedded reinforcement that was included in the interface. By excluding the interface elements, the longitudinal stress distribution in the roots was typical of a pull-out test (Dupuy et al., 2005b) with the peak occurring at the zone of shearing. Furthermore, this discrepancy could be a result of the full bond specified between the individual roots and the soil, and the allowance for soil deformation in 3D and flow between individual roots. However, the embedded reinforcements (vertical piles) used to model the multi-rooted soil in Diana® can simulate root geometry better than the 2D plane strain 'sheet' representations. The allowance of 3D soil flow between the roots closely resembles reality and is an advantage of the 3D approach over the 2D model where, due to the intrinsic model characteristics, the soil was effectively confined between the line elements representing roots. To further validate the 3D multi-rooted results, an investigation using structural line elements, such as truss elements in Diana®, could be performed for the simple vertical root systems considered in this study. Future studies could also explore the effect of a tension cut-off inclusion for the analyses in Diana®.

As previously reported in the literature (Waldron, 1977; Shewbridge and Sitar, 1996; Abe and Ziemer, 1991; Fan and Su, 2009a,b) and predicted by the numerical models, the inclusion of root analogues in the in situ tests contributed to a marked increase of shear resistance of the root–soil medium. Furthermore, the in situ shear tests qualitatively confirmed the results obtained through numerical modelling: the soil with analogue roots inclusion showed much more ductile response than the fallow soil – the response closely resembling the one predicted by the numerical models.

The validity of the results of the in situ shearbox tests as well as the justification for the choice of in situ test soil mix were verified by a comparison against laboratory shearbox tests. The differences between the soil properties of the modelled soil and the in situ mix, notwithstanding the higher bulk density of the in situ packed soil, are due to the relatively low percentage of clay in the mix and the imperfections and non-homogeneities during the packing of the soil in the in situ shear box. The tests showed that the variation in the strength properties measured in situ and in laboratory was minimal. The in situ tests showed that the inclusion of root analogues resulted in an increase in the effective cohesion of the root–soil continuum, with a magnitude falling within the range quoted in the literature (Norris et al., 2008). There was also a minimal decrease in the angle of internal friction observed with the rooted soil when compared to fallow soil, but this was attributed to the disturbance and imperfections of compaction around the analogue roots. However, the physical impossibility of replicating material and strength properties for the soil medium and the roots used in the numerical models precluded direct comparison of the modelled and the values of peak shear stress obtained from the in situ tests.

Mickovski and van Beek (2009) carried out direct shear box tests in situ at the same site (near Almudhaina, Spain), where data for root and soil characteristics were collated and used as input in our numerical models. Although Mickovski and van Beek (2009) investigated the contribution of vetiver grass (*Vetivaria zizanoides*) to soil shear strength, we can compare results from both field tests (Fig. 11b) and model simulations. The closest result for non-rooted soil was obtained from the Diana® 2D model with interfaces and tension allowed (7.5 kPa compared to 6 kPa measured in situ). The Plaxis® 2D model with interfaces and tension allowed, predicted a higher shear stress of 8.7 kPa. The Plaxis® 2D multi-rooted analysis with interfaces and no tension allowed predicted a shear stress of 13.3 kPa compared to the 10 kPa measured in the field. Although values are comparable, the differences between the shear resistance measured in situ and model simulations may be due to differences in root distribution between the modelled and real plants, as well as to the possible differences in the level of moisture

content and homogeneity of the soil in situ. Future work therefore could investigate the influence of different spatial distributions of roots within soil subjected to shear and also the influence of soil hydrological conditions.

The modelling approach presented in this technical paper could be used for verification of the assumptions made in other rooting models such as the perpendicular root model (Wu et al., 1979) or the Fibre Bundle Model (Pollen and Simon, 2005). Shear zone thickness can be assessed from the total stress and plastic point distribution (Fig. 7) and thus refine the assumptions made in Wu et al.'s (1979) and Pollen and Simon's (2005) models. We also showed that the behaviour of the root reinforced soil can be successfully modelled using existing and widely available FE codes where only the material properties and the distribution of the roots are known. Although both of these parameters are species specific and highly variable, they can be assessed, if nothing else than for a first approximation, from already published data (e.g. Gray and Sotir, 1996; Coppin and Richards, 1990; Norris et al., 2008; Schwarz et al., 2010). However, accurate information about the quantitative effects of roots on soil strength is necessary to guide the design and management of stabilisation systems that incorporate a vegetative element, and data from species suitable for field applications is essential.

The numerical models, qualitatively validated by the findings of the in situ tests, showed that the effect of roots on the shear behaviour of soil can be effectively modelled with inclusion of structural elements with simple geometry. Acknowledging the natural variability in root material and strength properties and carrying out more detailed investigation of more species used in eco-engineering practices would ultimately lead to more certainty in the choice of model parameters. Simplifying the root system geometry by modelling only the main structural roots and their behaviour during shear, while neglecting the strengthening effect of the smaller roots and branching, will provide a 'factored down' strength of the root–soil continuum suitable for use in engineering design (e.g. slope stability). Further field research and verification against refined numerical models, however, will be needed in order to determine the range of this 'factoring down'.

Acknowledgements

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